INVESTIGATING SPATIOTEMPORAL DISTRIBUTION AND HABITAT USE OF POORLY UNDERSTOOD PROCELLARIIFORM SEABIRDS ON A REMOTE ISLAND IN AMERICAN SAMOA

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Nature is always lovely, invincible, glad, whatever is done and suffered by her creatures. All scars she heals, whether in rocks or water or sky or hearts.

- John Muir

If it's your job to eat a frog, it's best to do it first thing in the morning. And if it's your job to eat two frogs, it's best to eat the biggest one first.

-Mark Twain

Ethical behavior is doing the right thing when no one else is watching - even when doing the wrong thing is legal.

- Aldo Leopold

DEDICATION

This dissertation is dedicated to my wife Alexis Rudd for her unwavering support and belief. Thank you for the pep talks, the many checklists, and reminders about frogs.

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ABSTRACT

Seabirds are important components of marine and terrestrial ecosystems across the globe, ranging across all oceans, adapted to all environments, and using both marine and terrestrial ecosystems. The island of Taʻū in American Samoa is not well studied, yet is home to a potentially significantly important breeding population of a suite of Procellariiform seabirds, the Tahiti Petrel (*Pseudobulweria rostrata*), and Tropical Shearwater (*Puffinus bailloni*). Because many of these birds are difficult to locate and study due to their nocturnal nature, and nesting locations in burrows at the top of a mountainous remote island, Automated Recording Units (ARU) provide a useful tool to learn about these species. I investigated the differences in detection probability for ARUs under different habitat and environmental conditions. Further, I used automated recording units to determine the spatiotemporal activity patterns of a suite of seabird species over the summit area of Taʻū. Finally, I used a Species Distribution Modeling approach to determine the habitat, physical, and environmental characteristics that affect Tahiti petrel nesting presence and the distribution of suitable habitat across the summit region of Taʻū. Detection ranges of ARUs varied from < 10 m in high wind conditions, up to 90 m in low wind conditions. On Taʻū, Tahiti petrel was the most widespread species and showed spatially and temporally different levels of acoustic activity from Tropical shearwater. Activity for Tahiti petrels was highest in April – May while Tropical shearwaters were more active in December. Tahiti petrel nesting location on Taʻū were best predicted by closed canopy cover and higher altitude. Of a total of 774.1 ha of montane habitat on Taʻū, 63.8% was covered by canopy tree species and a total of 254.1 ha was classified as most suitable for petrel nesting. These findings present evidence of the usefulness of ARUs, particularly in challenging environments. Further,

these findings advance our knowledge of the ecology, behavior, and life history of data-deficient species in American Samoa and has implications for the management of these species and the montane habitat on Ta‘ū.

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CHAPTER 1. INTRODUCTION – ECOLOGICAL ROLE OF PROCELLARIIFORM SEABIRDS AND NOVEL TECHNIQUES FOR STUDYING CRYPTIC SPECIES

Introduction

An extremely diverse group of birds spanning 14 families within 4 orders, most seabirds are generally considered to be upper trophic level predatory species which rely on marine resources for breeding purposes. Some species of Laridae, Pelecanidae, Phalacrocoracidae, and Sternidae are excluded from the seabirds because they either breed inland or rely on freshwater resources. All told, there are 328 species of seabirds (Hamer et al. 2001). Found in marine and coastal habitats throughout the world, seabird species are adapted to fill foraging niches throughout the oceans, from shorelines to the most remote pelagic regions. These ocean environments are extremely large and heterogeneous, with seabirds taking advantage of resources that are often patchy and unpredictable (Schreiber and Burger 2001, Weimerskirch 2007).

Seabirds have adapted both morphologically and physiologically to live and breed in habitats across the globe and have developed a range of life history strategies and foraging techniques to take advantage of a large range of marine habitats, from the tropics to the polar regions. For example, penguins have evolved high fat storage capacity and special blood circulation processes to adapt to extreme cold environments, and are flightless but can dive to depths of over 700 m in pursuit of prey (Le Maho 1977, Kooyman and Kooyman 1995). In contrast, albatrosses nest on oceanic islands and have evolved wingspans of up to 4 m, which, coupled with a flight method called dynamic soaring leads to extremely low energy requirements while in flight (Weimerskirch et al. 2000). This low energy flight cost allows

albatross to travel across entire ocean basins, and 1000's of km in search of food resources which collect at oceanographic fronts and convergence zones.

While seabirds are an extremely diverse group, they all share some life history traits, particularly that they are long lived, have high adult survival, and low reproductive rates (Schreiber and Burger 2001). Many species live longer than 30 years, with the oldest known albatross in excess of 60 years and still breeding. Many species raise a single offspring at a time, and do not breed until at least age 3. In some cases, such as for many albatross species, breeding occurs only every other year (Jouventin and Dobson 2002). However, over their long life spans, seabirds can raise many successful offspring, even taking into account breeding failures.

The low reproduction rate observed in many seabird species is thought to be explained by the energy limitation hypothesis (Lack 1968, Reid et al. 2000, Hamer et al. 2000). Seabird colonies tend to deplete resources closest to the colony first, forcing the birds to forage further and further away. Paired with variability and inherent patchiness in food resources, it is difficult for seabirds to reliably provide the necessary nutrients to support multiple chicks (Lack 1968, Ashmole 1971). Despite this energy limitation, feeding niche partitioning may partially explain the ability of multiple seabird species to live and forage in the same ocean areas. For example, seabird populations in the Farallon Islands exhibit feeding niche partitioning during times of resource scarcity such as El Niño events (Ainley and Boekelheide 1990). Similarly, on the island of South Georgia, sympatrically breeding seabird species forage on the same species of krill, but segregate based on krill size (Croxall et al. 1997). The low reproductive rate of seabird species, along with small populations and restricted numbers of breeding sites means they are then

vulnerable to change and threats such as predation, invasive species, and habitat loss (Croxall et al. 2012).

While the importance of seabirds as apex predators in shaping marine ecosystems is well understood, seabirds are also an important component in shaping terrestrial ecosystems, and serve as a link between marine and terrestrial environments. The presence of seabird colonies can greatly influence the structure and health of terrestrial ecosystems. Particularly on islands, seabirds play an important role in nutrient cycling by importing large amounts of marine nutrients into terrestrial systems through the deposition of guano (Burger et al. 1978, Polis and Hurd 1996, Wainwright et al. 1998). This key link between terrestrial and marine ecosystems can stimulate primary productivity, structure plant communities, and shape terrestrial food webs (Croll et al. 2005, Hutchinson 1950, Anderson and Polis 1999).

One group of seabirds that are particularly interesting because of their life history characteristics are the tubenose species within the order Procellariiformes. This order contains all the albatrosses, petrels, shearwaters, storm-petrels, and diving petrels. The Procellariiformes are long lived, highly pelagic, and many are cryptic (Onley and Scofield 2007). Many of these species are among the most pelagic of all seabirds, foraging, and traveling over entire ocean basins. Because of these traits, only cursory information about their biology, range, and breeding distribution is known. Many species of petrels and shearwaters do not need to breed close to their foraging areas, are found on remote and difficult to access islands, and nest in burrows, explaining the data deficiencies (Warham 1990, Towns et al. 2011). It has been suggested that breeding on remote islands has been an evolutionary response to avoid terrestrial predators (Lack 1954, Furness and Monaghan 1987).

Burrow Nesting Seabirds

Predation avoidance plays a role in many aspects of seabird reproductive strategies. The overwhelming majority of seabirds breed in colonies or groups of breeding individuals (Coulson 2001). While there are many reasons for group breeding, one is that is serves as a defense against predation. For instance, large colonial nesting by Arctic Terns (*Sterna paradisaea*) and Common Terns (*Sterna hirundo*) reduce predator effectiveness (Hamilton 1971). Beyond serving as a defense against predation, there are also indications that seabird colonies provide social benefits such as the spreading of information. The modified Information Center Hypothesis (Ward and Zahavi 1973) proposes that individual birds learn about optimal foraging locations by following successful birds to their foraging locations (Coulson 2001).

Seabirds use many nest types, including crevices, cavities, tree hollows, surface nests, and burrows. Burrow and cavity nesting seabirds include most of the smaller Procellariiformes, five penguin species, tropicbirds, and 18 Alcidae species (Bried and Jouventin 2001). The quality of the nesting sites within the colony vary based on location, with nests in the periphery of the colony generally being less productive (Rowley 1983) and having higher predation rates (Carrick and Ingham 1967). The presence of multiple sympatrically breeding species can lead to interspecific competition for nest sites, and the partitioning of the colony area (Buckley and Buckley 1980). Burrow nesting also provides protection and concealment of the nest from predators. Burrow nesting can also facilitate higher population densities within the colony, and allows multiple species with different breeding strategies to use the same colony area. High density, multi-species colonies are particularly important given that many burrow nesting

species nest on small islands, where space is often limited, necessitating high population densities and nest site partitioning.

Many burrowing seabirds, and Procellariiformes in particular, are philopatric, exhibiting high site as well as mate fidelity, returning to the same burrow to breed year after year with the same partner (Bried and Jouventin 2001). Site and mate fidelity allow for an increase in breeding success due to increased coordination among mates with regards to feeding schedules and incubation (Choudhury 1995). Because competition is high among many burrowing Procellariiformes, fidelity to burrows can reduce competition and allow for individual birds to better defend their territory (Warham 1990). Having stable, long-term neighbors within the colony also may reduce competitive interactions, both in number and severity (Falls and McNichol 1979, Stamps 1987).

The burrow can also serve as a meeting point in the colony, allowing birds to maintain pair bonds from year to year (Morse and Kress 1984). These benefits do not come without costs however. For example, burrowing seabirds are liable to incur breeding costs while waiting for their mate. Because the pair bond often dissolves during the non-breeding season, when the birds return, they must wait for each other at the burrow to re-establish their bond and mate (Bried and Jouventin 2001). When pair bonds in these birds are dissolved through loss of an individual, or breeding asynchrony, re-pairing is a prolonged process that can take years (Gochfeld 1980, Jouventin and Weimerskirch 1984, Bried and Jouventin 1999). For instance, female Laysan albatross (*Phoebastria immutabilis*) pairing with new inexperienced males can exhibit difficulties in synchronizing courtship and delaying breeding (Van Ryzin and Fisher 1976). A further complication is the phenomenon of sabbatical years often seen in

Procellariiformes. When a partner is on sabbatical and does not return to the colony, the other bird may switch partners as in Cory's shearwater (*Calonectris borealis*; Mougin et al. 1987a, b). Sabbaticals also leave the valuable nesting site unoccupied to be colonized by other prospecting, or nest switching birds. If a nesting territory is already occupied when the original owners return, it can cause a failure to breed and dissolution of the pair bond (Dhondt and Adriaensen 1994).

The vast majority of seabird species are diurnal (Del Hoyo et al. 1992). An exception to this circadian rhythm are the petrels, which as a group are mostly nocturnal when present at their colonies (Warham 1990, Del Hoyo et al. 1992). This nocturnal behavior, along with an avoidance of the colony during the full moon is thought to be in part a predator avoidance technique (Watanuki 1986, Bretagnolle 1990, Brooke and Prince 1991, McNeil et al. 1993 Mougeot and Bretagnolle 2000). In fact, approximately 90% of the Procellariiformes, and 30% of the Alcidae nest in burrows or crevices, and are nocturnally active at the colony, spending daylight hours at sea, or staying within the burrow (Lack 1968, Brooke 1990, Brooke and Prince 1991, Gaston and Jones 1998). While predator avoidance is most likely the obvious benefit of these two life history traits, the evolution of island nesting itself is likely due in part because islands were refuges from predators (Furness and Monaghan 1987). While it is true that islands often provide a refuge from mammalian predators, there are other predation risks that the evolution of island nesting cannot protect against. For instance, the Black-vented shearwater (*Puffinus opisthomelas*) in Mexico is at risk from predation by the Western gull (*Larus occidentalis*), and the European storm-petrel (*Hydrobates pelaicus*) is preyed upon by the Yellow-legged gull (*Larus michahellis*) (Keitt et al. 2004, Oro et al. 2005). Similarly, on sub-

Antarctic islands, Skuas (*Stercorarius* spp.) have become specialist predators on burrow dwelling petrels (Young 1978, Jones 1980, Moors 1980, Fraser 1984, Mougeout et al. 1998).

Burrow and crevice nesting seabirds also use their burrows as a refuge and protection from weather (Brooke 2004). Because these birds tend to be smaller (crevice nesters average 40g – 200 g, burrow nesters average 20g – 600 g; Veit and Jones 2003, Smith et al. 2011), they are less likely to be able to withstand storms, large swings in temperature, or other extreme weather events. In temperate and tropical environments, the burrow provides important temperature regulation for the chicks, protecting them from the effect of extreme temperatures. Many burrow nesting species leave chicks unattended for days due to extended foraging trips, or the inability to return due to severe storms (Boersma et al. 1980). Burrows can prevent the chick from expending too much energy on its own thermoregulatory needs and allows the chick to maximize growth (Brooke 2004). Fork-tailed storm-petrel (*Oceanodroma furcata*) chicks experience a wide range of temperatures, from 10°C to 40°C, with body temperatures dropping very low for extended periods without feeding (Boersma 1986). The thermoregulatory benefit of burrows should not be underestimated. In tropical heat, burrows provide a thermoregulatory benefit for Wedge-tailed shearwater (*Puffinus pacificus*) chicks (Whittow et al. 1987). In another Procellariiform species, Laysan albatross chicks which are in surface nests, can die from dehydration (Sileo et al. 1990). This dehydration is caused by the long periods of time chicks must endure between feeding bouts, and the hot conditions they encounter at their surface nests, with adults and chicks exhibiting body temperatures of almost 40°C (Howell and Bartholomew 1961). Abnormally high temperatures and high rain levels can also cause mortality and breeding failures in ground nesting seabirds. For example, Thick-billed

murre (*Uria lomvia*) nesting sites in the northern Hudson Bay, Canada that are exposed to high temperatures and afternoon sun showed breeding failure and adult mortality (Gaston et al. 2002). Additionally, Manx shearwater (*Puffinus puffinus*) on the Isle of Rum, Scotland exhibit significantly lower hatching success after periods of heavy rain (Thompsoan and Furness 1991).

While burrow nesting seabirds derive many benefits from their nesting strategy, burrowing behavior causes a high amount of disturbance, destruction, and modification to the environment. Burrows can be very long, up to 3 – 5 m in the case of Sooty shearwaters (*Puffinus griseus*), and can reach high densities with 18 – 34% of the ground surface tunneled (McKechnie 2006). Burrowing results in many detrimental effects on the surrounding environment including a reduction in soil integrity, low soil pH, high soil phosphorus levels, increased litter deposition, root damage to plants, and lower seedling recruitment (Mulder and Keall 2001, Burger 2005, Grant-Hoffman et al. 2010a, b). Birds can cause extensive damage to vegetation as they climb, land on, and move through the surrounding habitat (Brooke 2004, McKechnie 2006). Because of the high site fidelity of many burrow nesting species, soil erosion issues may become exacerbated over time, with birds enlarging burrows in each nesting season, creating further soil instability (McKechnie 2006).

Burrow nesting seabirds overall are a unique group of species that have specifically adapted their nesting strategy to counteract any detrimental effects they would incur from their foraging strategies, their small size, and vulnerabilities to predation. This strategy does come at a cost to the structure, stability, and condition of the surrounding environment. While seabirds can play a significant role in nutrient deposition within their colony areas (Allaway and

Ashford 1984, Mulder and Keall 2001, Zwolicki et al. 2013), the amount of change and damage that burrowing seabirds can enact on their environment is enormous.

Seabird Communication

Communication in seabirds is important, in part because they breed in colonies with high densities where they must interact with other birds in close proximity, and be able to locate their nest site. Because of this close proximity, there is a high amount of physical and acoustic display within seabird colonies (Nelson and Baird 2011). Although the majority of seabirds have the same modified tympaniform membranes within the syrinx that would allow for the same sound production as songbirds (Greenewalt 1968), most seabird calls are more limited in structure and complexity than their songbird counterparts (Nelson and Baird 2011). Despite this apparent simplicity, calls are complex and unique enough among individuals that parents can recognize their offspring (Lefevre et al. 1998, Jouventin et al. 1999).

Because the majority of the Procellariiformes are nocturnal and nest in burrows, visual displays are less common than vocalizations (Storey 1984, James 1985, Bretagnolle 1996, Nelson and Baird 2011). Males call from burrows to compete with other males for the attraction of females, as in the case of Manx shearwaters. Male Blue petrels (*Halobaena caerulea*) call from the ground while females call on the wing before landing (Storey 1984, Bretagnolle 1990b). Generally, Procellariiformes have one or two major calls for courtship and pair-bond maintenance, and one or more minor calls used for food-begging, copulation, agonistic, distress, and contact (Bretagnolle 1996). Given that acoustic signals are the dominant form of communication in Procellariiform seabirds, it might be expected that their call

repertoire would be larger than that of other seabirds which use a combination of calls and visual displays for communication. In contrast, songbirds have much larger repertoires, likely due to the larger numbers of minor calls, possibly used to convey less important information (Bretagnolle 1996).

Based on the spectrograms of 32 petrel species, Bretagnolle (1996) was able to summarize the acoustic structure characterizing petrel vocalizations. A great diversity in the structure of calls among species is present, but the majority of species have a fundamental or base frequency and harmonics present. Most calls, except for those of *Pseudobulweria,* lack rapid amplitude modulation (Bretagnolle 1996). Other than some *Procellaria* calls, most also lack rapid frequency modulation (Brooke 1986, Warham 1988). Calls are separated into distinct syllables which are usually stereotyped and can be varied in duration (Bretagnolle 1996).

Seabird colonies are noisy places, both due to the density of birds, and to environmental wind, surf, and rain (Robisson 1991, Bretagnolle 1996, Aubin and Jouventin 1998). Sounds undergo distortion and degradation as they propagate, modifying the frequency spectrum of the sound (Bradbury and Vehrencamp 1998). A major component of the loss of sound intensity occurs through global attenuation, in which a spreading loss of 6 dB of pressure occurs for each doubling of distance that the sound travels. This loss of intensity occurs because as a sphere of sound spreads, the number of molecules the energy is being transferred to increases, resulting in a decrease in the amount of energy transferred to any one molecule (Bradbury and Vehrencamp 1998). Pattern loss by absorption causes a filtering of certain frequencies during propagation. Since medium absorption increases linearly with frequency, the high frequency

components of a signal are reduced more than other frequencies and do not travel as far (Bradbury and Vehrencamp 1998).

Signal components can also be subject to scattering from the objects they encounter in the environment. In a biological context, these objects can often come in the form of vegetation, with the amount of scattering depending on the size and density of the leaves and trees. Estimates of the pattern loss range from 2-35 dB/100 m (*f* = 1-10 kHz) in broadleaf forests, to 2-20 dB/100 m (*f* = 1-10 kHz) in coniferous forests (Marten and Marler 1977, Marten et al. 1977). Differences in air densities due to heating and cooling as well as pressure differences caused by wind can also significantly add to the pattern loss. In open areas with no wind, attenuation from medium absorption can be 1-12 dB/100 m (*f* = 1-10 kHz) (Wiley and Richards 1982). Additionally, wind can add 2-200 dB/100 m (*f* = 1-10 kHz) of broadband noise which can mask the signal. Finally, refraction can add to pattern loss, with high winds bending the sound up into the wind and creating sound shadows on the ground (Bradbury and Vehrencamp 1998). Because of these environmental challenges, it would be expected that petrel calls would be structured to improve detection probability and to reduce attenuation in their noisy environments (Wiley and Richards 1982, Robisson et al. 1993). It is likely that the need to communicate within these complex and noisy environments is why many petrel calls cover a wide frequency spectrum with many harmonics, wide band noise, and call repetition (Wiley and Richards 1982).

Petrels and shearwaters use calls to communicate between males and females (James and Robertson 1985, Brooke 1990), defend territories and burrows (Bretagnolle and Lequette 1990), and select mates (Krebs and Kroodsma 1980). Because all species are using the same

limited repertoire of calls, individuals are able to detect small differences in the temporal pattern and frequency of the calls. For example, an analysis of the calls of Blue petrel and Cory's shearwater show that information on the fitness of the individual is often coded within temporal parameters at the end of the call (Genevois and Bretagnolle 1994, Bretagnolle and Lequette 1990). Additionally, geographic differences can be seen in both temporal parameters and frequency parameters within the call, and sexual information can be perceived from differences in the syntax of the call (Genevois and Bretagnolle 1994, Bretagnolle and Lequette 1990). This would indicate there is a lot of information encoded within the limited repertoires of both Procellariiform calls, and also seabird calls in general.

Using Acoustics as a Tool for Avian Study

An understanding of petrel and shearwater acoustic communication is important because passive acoustic methods can be leveraged as a useful technique for studying these cryptic species in remote locations. Passive acoustic methods refer to the use of recording devices which capture the sounds emitted around them. Particularly, passive acoustic observations can be used to study the identity, distribution, and location of animals by capturing and identifying sound produced within the environment (Mellinger et al. 2007). These techniques have been developed over the past 35 years and are now widespread, particularly in the study of cetaceans (Moore et al. 2006, Zimmer 2011, Marques et al. 2013). Passive acoustic methods are particularly useful in cetacean studies because it is difficult to detect animals that spend the majority of their time underwater through the use of visual survey techniques that only detect them at the ocean surface (Mellinger et al. 2007). Visual surveys have other

limitations such as being restricted to daylight hours, and periods of good weather (Mellinger and Barlow 2003). Also of concern has been the issue of human observer bias that has been addressed for all types of wildlife surveys, from marine mammals to amphibians and birds (Marsh and Sinclair 1989, Diefenbach et al. 2003, Lotz and Allen 2007). Remote technologies such as unmanned aerial vehicles, passive acoustics, and motion activated cameras, along with greater data processing capabilities have allowed wildlife biologists to remove a lot of this human bias in addition to extending the spatial and temporal coverage of sampling effort (Mellinger et al. 2007, Rowcliffe and Carbone 2008, Linchant et al. 2015).

Passive acoustic techniques allow for data collection to occur throughout the day and night, and across a large range of weather or other environmental conditions. Passive acoustic techniques can also be beneficial when species are small, cryptic, or otherwise difficult to study using traditional methods (Marques et al. 2013). For example, many terrestrial animals that may spend a majority their time underground, are nocturnal, camouflaged, or live in thick foliage are particularly suited to the use of alternative methods (Marques et al. 2013). Further benefits of passive acoustic techniques are that large amounts of data can be collected over spatial and temporal scales in a standardized way that eliminates the variance usually seen in visual observer studies (Marques et al. 2013). Long deployments of passive acoustic devices are also a cost-effective solution as they decrease the amount of time scientists need to spend in the field, and the devices do not require extensive training to deploy and maintain.

In avian ecology, single microphone units have been used to determine species richness and composition (Haselmayer and Quinn 2000). More complex stereo microphone units and quadraphonic microphone arrays can be used to estimate species abundance, richness, and

community composition (Hobson et al. 2002, Cellis-Murillo et al. 2009). Microphone arrays can use the time difference of arrival of the acoustic signal to localize individuals within a study area (Collier et al. 2010).

Because seabirds are vocally active and predictably return to geographically defined nesting colonies, they are ideal candidates for using passive acoustic techniques to investigate distribution, abundance, and trends over time. Passive acoustic techniques are also valuable for seabird studies because nesting colonies are often on islands, remote locations, or are otherwise difficult to access. Because some seabirds are nocturnal at the colony and nest in burrows, they are ideal species to be studied using passive acoustics. Procellariiform seabirds, which are nocturnal and communicate primarily through the use of calls, are more readily studied via acoustic than visual methods (Bretagnolle 1996, Robb et al. 2008).

Autonomous recording units (ARUs) are increasingly used to study the presence, distribution, and relative activity of seabirds in remote locations. In Alaska, ARUs have been used to detect the activity of Marbled murrelet (*Brachyramphus marmoratus*) and Kittlitz's murrelet (*Brachyramphus brevirostris*) on Kodiac Island (Cragg et al. 2016). In the Aleutian Islands, ARU's have been used to compare activity of Leach's storm-petrel (*Oceanodroma leucorhoa*), Fork-tailed storm-petrel, and Ancient murrelet (*Synthliboramphus antiquus*; Buxton and Jones 2012, Buxton et al. 2013). Following the eradication of invasive predators on Anacapa Island in California, ARU's were used to compare activity of Leach's storm-petrel, Ashy storm-petrel (*Oceanodroma homochroa*), and Cassin's auklet (*Ptychoramphus aleuticus*) over time (Croll et al. 2016, Harvey et al. 2016, Newton et al. 2016). Many studies using ARU's thus far have focused on measuring calls recorded per unit time, a metric of seabird activity. Some work

has also been done to better understand the capabilities of the units, estimate the number of birds recorded, and better identify calls from recordings. For instance, Borker et al. (2014) found that the number of Forster's Tern (*Sterna forsteri*) calls in a colony correlate with the number of birds present. For Cory's shearwater, there was a correlation between the number of calls recorded and the number of burrows (Oppel et al. 2014). Studies have also investigated how the distance of ARU's from the bird influences the number of calls detected (Cragg et al. 2015). A large variety of methods are used to detect calls within acoustic data including energy summation, image processing, and neural networks (Potter et al. 1994, Oswald et al. 2004, Gillespie 2004). Increasingly, sophisticated machine learning approaches are being developed that aid in the detection of seabird calls within the large amounts of data that ARU's can generate (Dufour et al. 2016).

Knowledge Gaps

Seabirds in the central South Pacific Ocean are generally poorly studied. In particular the region of tropical South Pacific Islands is the least represented when considering publications on seabird colony restoration and the role of seabirds as ecosystem engineers (Ellis 2005, Jones et al. 2011). The South Pacific is such an understudied region because it is mostly made up of developing island nations with low levels of infrastructure and investment in science. In addition, Pacific Islands are generally small, remote, and difficult to access. Nevertheless, Pacific Islands generally exhibit high rates of endemism, diversity, and species richness in both terrestrial and marine ecosystems (Dinerstein and Wikramanayake 1993, Bowen et al. 2013). Because of these research challenges, there are still many significant gaps in our knowledge of

the biota across the entire region. In particular, petrel and shearwater species which breed, feed, and are only found in the South Pacific are poorly understood. Many of these species are difficult to study in their own right due to their cryptic characteristics, nocturnal activity on the colony, and burrow nesting strategies including extreme terrain nesting locations. Many methods have been developed to study the distribution, phenology, and life history of cryptic seabird species that breed in remote, difficult to access locations, including tracking, radar, isotopic analysis, and acoustic monitoring (Wakefield et al. 2009, Gauthreaux and Belser 2003, Bond and Jones 2009, McKown et al. 2012).

Islands in the South Pacific that host multiple species of Procellariidae present opportunities for expanding our knowledge not only of the poorly understood biota, but to examine the behavior and habitat interactions of these secretive species. American Samoa is an unincorporated territory of the United States located in the South Pacific and although we know little about the seabirds of American Samoa, the territory provides potentially valuable breeding habitat for several near threatened and poorly known seabird species (O'Connor and Rauzon 2004). Amongst the American Samoa chain, the heavily forested high volcanic island of Ta'ū in the Manu'a group is home to several species of Procellariiform seabirds, including Tahiti petrel (*Pseudobulweria rostrata*), Herald petrel (*Pterodroma heraldica*), Tropical shearwater (*Puffinus bailloni*), and possibly Polynesian storm-petrel (*Nesofregetta fuliginosa*; Amerson et al. 1982, Pyle et al. 1990). The Tahiti petrel is listed as near threatened by the International Union for Conservation of Nature (IUCN) and the Polynesian storm-petrel is listed as endangered, whereas the Herald petrel and Tropical shearwater are listed as species of least concern (Birdlife International 2012, 2014a, b). Very little is known about the status and

distribution of Procellariiformes on Ta‘ū, as few studies have been conducted (Amerson et al. 1982, O’Connor and Rauzon, 2004, Rauzon and Rudd 2014). Procellariiform seabird populations in American Samoa may face many threats including predation from rats and a loss of breeding habitat (O’Connor and Rauzon 2004).

Understanding more about Procellariiform species in American Samoa is important because this group of seabirds are generally both important components of the marine food webs and the island montane ecosystems where they nest. Within a conservation context, the effects of invasive species and predation are well understood on Procellariiform seabirds. However, when trying to understand the cumulative factors that affect population levels, understanding other impacts such as the variation in habitat structure, and inter-species interactions through niche partitioning in their breeding habitat is important because these factors affect the total population carrying capacity that the habitat can support. Passive acoustic monitoring techniques are ideal for investigating these factors, particularly within the heavily forested habitats found on Ta‘ū.

Goals and Objectives

This dissertation investigated how sympatrically breeding seabirds differentially use habitat, both spatially and temporally. Additionally, this dissertation determined how a single species of petrel, the Tahiti petrel is distributed based on terrestrial habitat characteristics. To address these questions I used passive acoustic methods, both a novel and emerging technique in seabird research. Thus, the specific objectives addressed in this dissertation are:

1. Investigate the differences in detection probability for Automated Recording Units under different habitat and environmental conditions (Chapter 2).
2. Determine the spatiotemporal patterns of Procellariiformes seabirds using ARUs in a remote island context (Chapter 3).
3. Determine what differences in habitat structure, physical characteristics, and environmental conditions affect the nesting presence and location of the Tahiti petrel (*Pseudobulweria rostrata*) in a tropical montane habitat (Chapter 4).

To investigate the applicability of passive acoustic sensors for surveying nesting seabirds I determined the detection distance of different call types for three species of seabirds under different habitat and environmental conditions. The second chapter has been written for submission to the *Auk*. To evaluate the second objective, I used a network of passive acoustic sensors to determine the spatial and temporal patterns of Procellariiform seabird habitat use on Ta‘ū over an altitude gradient, across summit regions with different habitat properties, and over time across different seasons. The third chapter has been written for submission to the *Journal of Animal Ecology*. Finally, to investigate nesting habitat preferences in further depth, I used a statistical modeling and GIS approach to model suitable nesting habitat for the Tahiti petrel (*Pseudobulweria rostrata*) and its breeding range over the summit montane region on Ta‘ū. The fourth chapter has been written for submission to *Biological Conservation*.

Table 1.1. Nesting sites used by seabirds (Reprinted from Schreiber and Burger 2001).

	burrow	crevice	boulders or rock cavities	tree holes	cliff ledges	trees	flat ground	steep slopes	no sites
Sphenisciformes	+		+				+	+	+
Procellariiformes	+	+	+		+		+	+	
Pelecaniformes									
Tropicbirds		+	+	+	+		+		
Sulids					+	+	+		
Frigatebirds						+	+		
Cormorants					+	+	+	+	
Charadriiformes									
Skuas and Jaegers							+		
Gulls and Terns		+	+		+	+	+		
Alcidae	+	+	+	+	+				

References: Nelson 1978, 1980, Warham 1990, del Hoyo et al. 1992, Furness 1996, Burger and Gochfeld 1996, Gochfeld and Burger 1996, Nettleship 1996, Gaston and Jones 1998.

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Appendix. Species Life Histories

Tahiti petrel (Pseudobulweria rostrata): The Tahiti petrel is a medium sized gadfly petrel with an average weight of 417-442 g and an average wing length of 297-302 mm (Villard et al. 2006). The Tahiti petrel is distributed across the southern tropical Pacific and breeds in loose colonies across many south Pacific islands. These breeding locations include the Marquesas, Society Islands, Gambier Islands (Thibault 1996, Thibault and Bretagnolle 1999), Fiji, New Caledonia, and American Samoa (BirdLife International 2014a; Figure 1). The species may have also previously been breeding on Vanuatu and may be present in the Cook Islands (Pratt et al. 1987, Brooke 2004). The total population of the species is estimated at 10,000 pairs and 30,000 individuals (Brooke 2004). Population sizes at each breeding colony appear to be quite small, with the largest colony perhaps being on Raiatea in the Society Islands with an estimate of several thousand pairs (Holyoak and Thibault 1984). Recent observations from the Society Islands indicate large population declines (Birdlife International 2014a), a trend which anecdotally seems to have been observed in American Samoa during this work as compared to previous observations (Amerson et al. 1982, O'Connor and Rauzon 2004).

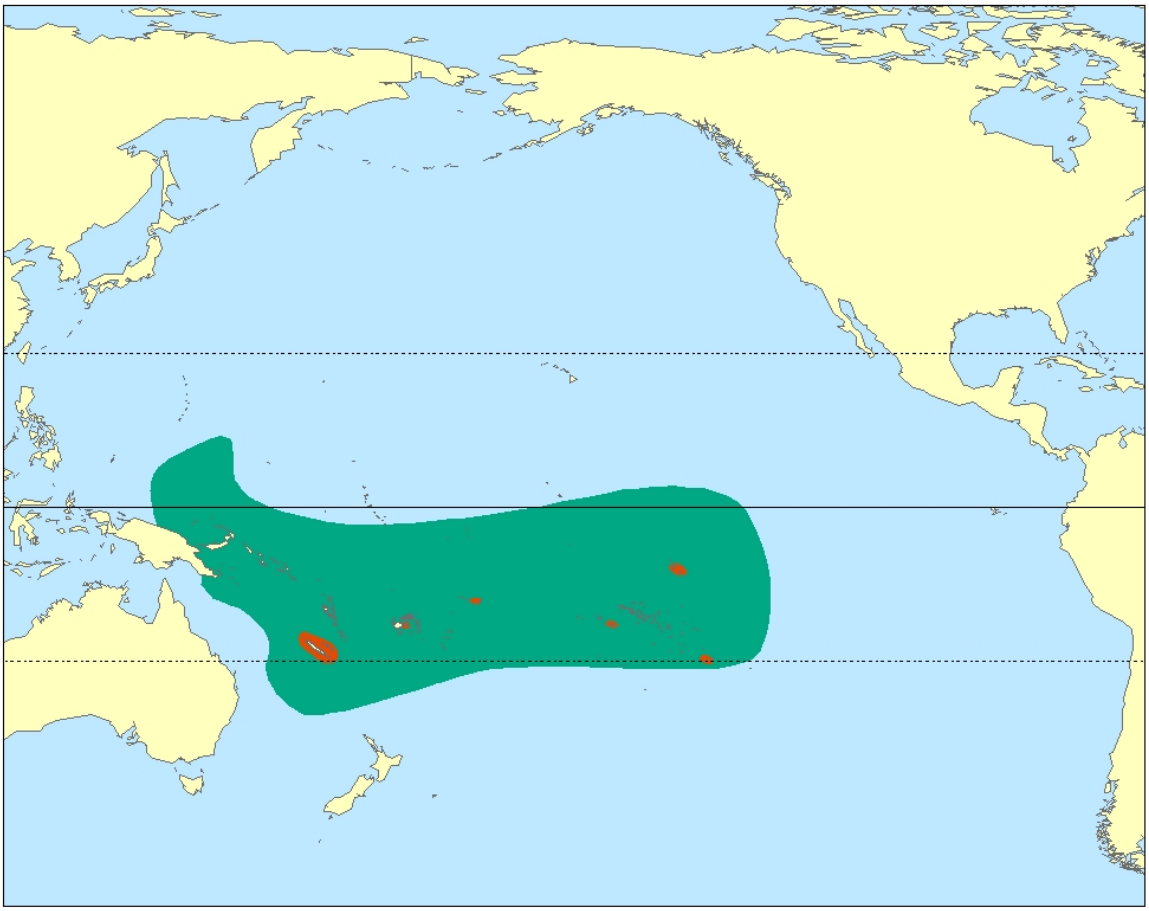

Figure 1.1. Distribution and breeding locations of Tahiti petrel (*Pseudobulweria rostrata*). Extent and breeding locations based on Onley and Scofield (2007) and BirdLife International (2014a).

There are few published studies on this species, so the biology, nesting habits, and phenology have been described mostly from colonies in the French territory of New Caledonia (Benoit and Bretagnolle 2002, Villard et al. 2006). Little is known about the ecology of these birds however most breeding seems to occur on high islands in open montane forest or on rocky slopes (Birdlife International 2014a). In New Caledonia, there appears to be breeding year round with a peak between March and July (Villard et al. 2006). Due to the tropical nature of this species and the wide geographic range of its breeding sites, it is likely that breeding does not follow a defined schedule and is tied to foraging resource availability around colonies.

Colonies are reported to be mostly small and in low densities, spread over large geographic areas (Clunie et al. 1978). Tahiti petrels likely face similar threats to many other island breeding Procellariiformes. Rat predation has been observed in the Marquesas and Society Islands (Birdlife International 2014a), and rats have been observed within colonies and burrows in American Samoa (O'Connor and Rauzon 2004, this study). Birds may also be threatened from other invasive predators such as wild pigs, feral cats, and dogs although the effects of these predators has not been quantified (Birdlife International 2014a). Light attraction at night is also an issue, with young birds attracted by lights around urban Papeete on Tahiti (Raust 1997). Grounding due to light attraction has also been reported previously in the urban areas of Tutuila in American Samoa (O'Connor and Rauzon 2004). This continues to be an issue in American Samoa with dozens of grounded birds handed into wildlife officials on Tutuila (MacDonald, personal comment).

Non-breeding dispersal seems to range across the tropical equatorial Pacific and subtropical South Pacific. Sightings have been recorded in the waters off Peru, Costa Rica, Mexico in the Eastern Pacific (Onley and Scofield 2007), and as far west as the Mozambique Channel in the Indian Ocean (Lambert 2004). It is not clear what the feeding habits are of this species, or where feeding occurs in the breeding vs non-breeding season. Many observations of Tahiti petrels have been made in association with the north equatorial countercurrent in the Eastern Tropical Pacific during regular NOAA cruises (Ballance et al. 2006).

The species is classified by the IUCN as near threatened due to its small and declining population, perhaps as a result of predation by introduced mammals (BirdLife International 2014a). Little is known about the biology of the Tahiti petrel generally, and within American

Samoa we lack knowledge of the species population size, distribution, and susceptibility to predation (O'Connor and Rauzon 2004). Due to its small and declining population size, the Tahiti petrel has been identified as a species of conservation concern. Estimating the abundance and distribution, and understanding the threats to this species has been identified as a priority in the comprehensive strategy for wildlife conservation in American Samoa (Department of Marine and Wildlife Resources 2006).

Tropical shearwater (Puffinus bailloni): The Tropical shearwater is a small dark and white shearwater with short broad wings and a long body. Average length is 27-33 cm, average weight is 165-259 g, and average wingspan is 64-74 cm. This species was previously a conspecific of Audubon's shearwater (*Puffinus lherminieri*) but was recently split from the Audubon's complex as taxonomists begin to better understand this wide-ranging group of shearwaters (Austin et al. 2004). There are four subspecies recognized including *P. b. nicolae* and *P. b. bailloni* in the tropical Indian Ocean, *P. b. dichrous* in the tropical Pacific Ocean, and *P. b. gunax* in the south west Pacific. The subspecies studied in this dissertation is *P. b. dichrous*. The Tropical shearwater has a wide range across the tropical, subtropical Pacific and Indian Oceans. In the Pacific, birds have been confirmed in French Polynesia, American Samoa, Samoa, Fiji, Kiribati, Federated States of Micronesia, Nauru, Northern Mariana Islands, Palau, Papua New Guinea, Tonga, Vanuatu, and the Solomon Islands. Tropical shearwater may occur on other Pacific Islands including the Marshall Islands, Niue, Pitcairn, Tokelau, Tuvalu, and Wallis and Futuna (BirdLife International 2014b; Figure 2).

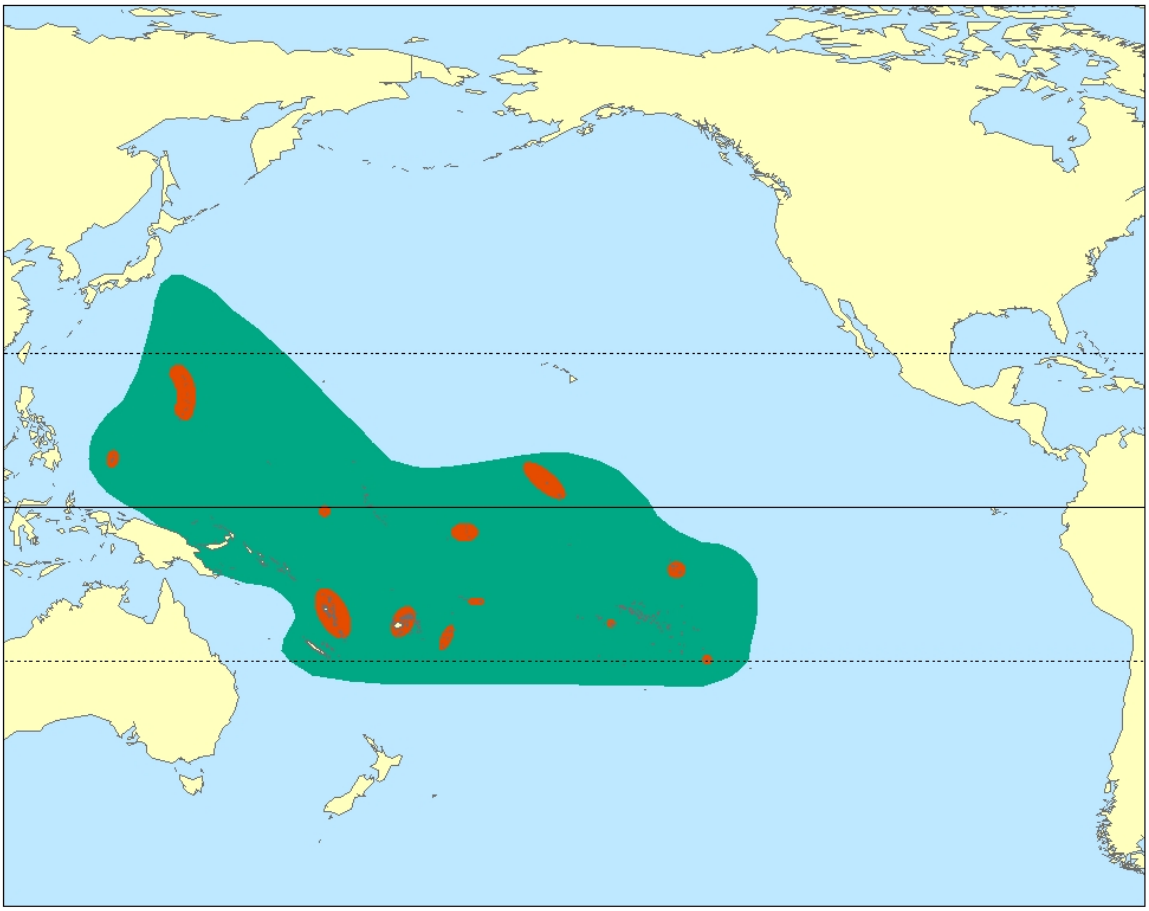

Figure 1.2. Distribution and breeding locations of Tropical shearwater (*Puffinus bailloni dichrous*). Extent and breeding locations based on Onley and Scofield (2007) and BirdLife International (2014b).

While the overall population size for either the Tropical Shearwater or the *P. b. dichrous* subspecies has not been quantified, it is thought that individual colonies can be quite large. The Line Islands support an estimated 1000-10,000 pairs, and the Phoenix Islands support an estimated 10,000-100,000 pairs (Brooke 2004). Overall population estimates are few and far between due to the taxonomic difficulties in the Audubon's shearwater complex. The extremely large range of the species along with large population sizes overall and at individual colonies means that the species is classified as least concern by the IUCN (BirdLife International 2014b).

Most of the taxa within the Audubon's complex are poorly studied. What is known about the phenology of this species is documented from the population breeding on Réunion Island (Jouanin 1970, 1987, Bretagnolle and Attié 1996). On Réunion Island, nesting is restricted to cliff areas, however, burrows were usually found at the base of the cliff (Bretagnolle et al. 2000). On Ta'u in American Samoa, Tropical shearwater are also nesting on the cliff area (Amerson et al. 1984) but nesting is not restricted to the base of the cliff as birds have been seen and heard from the top of the 950 m summit (O'Connor and Rauzon 2004, this study). Nesting is found in high montane habitats without canopy cover but not above 1,400 m (Bretagnolle et al. 2000). On Réunion, most Audubon's shearwaters arrived in August, laid eggs in October, and fledged between December and February (Bretagnolle et al. 2000). Tropical shearwaters are likely susceptible to the same threats that afflict other Procellariiformes such as predation by invasive species and habitat destruction (Collar et al. 1994). As with other Procellariiformes such as the Tahiti petrel (O'Conor and Rauzon 2004) and the Hawaiian petrel (Ainley et al. 1997), Audubon's shearwater also face a mortality threat from light attraction (Le Corre et al. 2002).

The species is pan tropical and found throughout the tropical and subtropical pacific, however the breeding and post breeding at sea distribution of the species is not well understood. Planktonic larvae and crustaceans make up the majority of the diet of Audubon's shearwater in the Galápagos (Harris 1969), but the feeding grounds of the species is not described.

The Tropical shearwater is not a species of conservation concern and is not currently threatened. There is a lack of knowledge however, due to general difficulties associated with

studying Procellariiform seabirds and the recent taxonomic work that split this species from the larger Audubon's complex. Due to the lack of knowledge about the species and the larger Audubon's shearwater complex, there is a need to better understand the morphology, life history, and calls of these birds (Austin et al. 2004).

Herald Petrel (*Pterodroma heraldica*): The Herald petrel is a medium sized *Pterodroma* petrel with a large bill and narrow wing. It is polymorphic, with light, intermediate, and dark phases (Onley and Scofield 2007). Average length is 34-39 cm, wing span is 88-102 cm, and average weight is 260-320 g. Herald petrels are found mostly in the central and western Pacific, breeding between Raine Island, Australia to the west and Easter Island, Chile to the east. The bird is known on many islands throughout the southern tropical Pacific including American Samoa (Pyle et al. 1990), Samoa, Kiribati, the Marshall Islands, the Federated States of Micronesia, Nauru, New Zealand, Niue, Papua New Guinea, the Solomon Islands, Tokelau, Tuvalu, Vanuatu, and Wallis and Futuna (BirdLife International 2012; Figure 3). The Herald petrel is very similar in plumage to the Trinidade petrel (*Pterodroma arminjoniana*) and both are polymorphic (Onley and Scofield 2007). Following the work of Brooke (2004), Herald petrel was split from Trinidade petrel along with the Henderson petrel (*Pterodroma atrata*) (BirdLife International 2012). The total population of the Herald petrel is estimated to be around 150,000 individuals (Brooke 2004), and the population is thought to be in decline. There are no good estimates for breeding colony sizes, and while some breeding colonies and islands are known, the wide range of the species means that the total number of colonies and their island locations are not well understood.

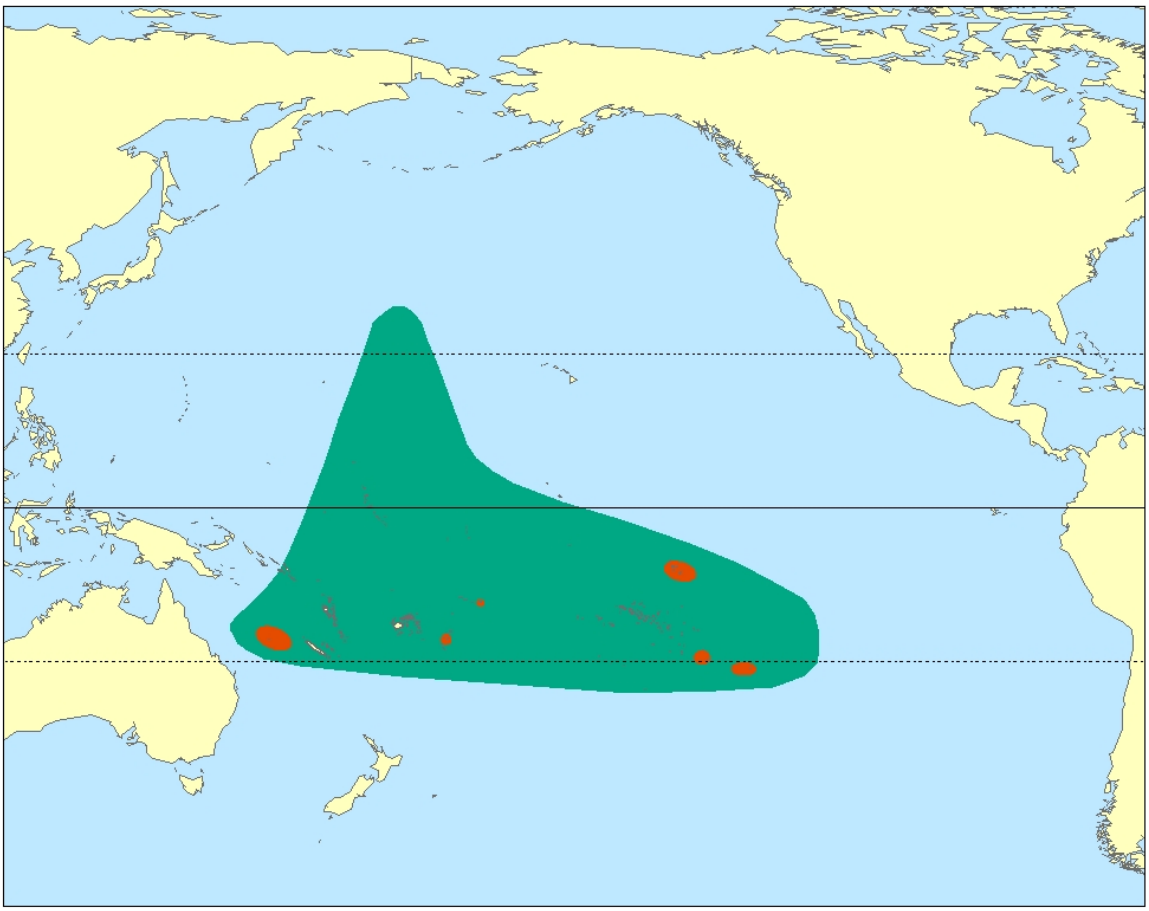

Figure 1.3. Distribution and breeding locations of Herald petrel (*Pterodroma heraldica*). Extent and breeding locations based on Onley and Scofield (2007) and BirdLife International (2012).

The Herald petrel is a highly pelagic species and while breeding is constrained to islands in the Southern Tropical Pacific, the species is noted at sea further away, including Hawaii in the northern sub-tropical Pacific. Little is known about the species foraging habitat or its diet, although squid have been recorded. As with other tropical and sub-tropical Procellariiformes, timing of breeding is variable based on location and is likely constrained by local food resource availability (BirdLife International 2012). Colonies are low in density with nests in rocky crevices, on crags, or on the ground under dense vegetation. Nests are found up to 1,000 m above sea

level (del Hoyo et al. 1992, Pyle et al. 1990, Brooke 1995, this study). Chicks of the related Henderson petrel in the Pitcairn Islands were reported to fledge in 91 days (Brooke 1995).

Herald petrel and Henderson petrel chicks in the Pitcairn Islands were reported to be at threat from predation due to invasive rats (Brooke 1995). Generally, for Procellariiformes seabirds, and other pelagic seabirds, invasive alien species, bycatch, and severe weather are the most prevalent threats (Croxall et al. 2012). Although the threats for the Herald petrel have not been properly assessed, population decline is suspected to at least be partially caused by predation and invasive species (BirdLife International 2012). Croxall et al. (2012) identifies increased understanding of population trends, and a better understanding of threats as priorities for research. Knowing the life history of this species including habitat preferences and breeding locations would be beneficial.

CHAPTER 2. AUTOMATED RECORDING UNIT DETECTION PROBABILITIES: APPLICATIONS FOR MONTANE NESTING SEABIRDS

Abstract

Passive acoustic techniques, through the use of Autonomous Recording Units (ARU) are useful for detecting the presence and distribution of cryptic and nocturnal animals in challenging, remote environments as they can be deployed for extended periods of time. In American Samoa, three Procellariiform seabird species nest on the remote island of Taʻū in difficult to access summit scrub habitat. This study investigated the differences in detection probability for two ARUs (Song Meter SM2 and SM4) under different habitat and environmental conditions. Detection ranges for seabird calls varied from < 10 m in high wind conditions, up to 90 m in low wind conditions. Under ideal conditions detection range varied from 40 to 100 m for Song Meter SM4 sensors and 40 to 70 m for SM2 sensors. Knowing the detection capabilities of ARUs will allow better design of sensor spacing, and a combination of acoustic recording with *in situ* weather data will allow for calculations of detectable areas and facilitation of determining animal densities.

Introduction

Passive acoustic survey methods, in which a device records the surrounding acoustic signals, are a useful alternative to visual survey methods in environments where species are visually cryptic and traditional visual surveys would be difficult, expensive, or dangerous (Dawson and Efford 2009, Marques et al. 2013). Advances in technology mean that Autonomous Recording Units (ARU) can be deployed in logistically and environmentally challenging, remote environments, and can operate unattended for months. The ability to collect long term data and monitor nocturnal species is one of the greatest benefits of remote acoustic monitoring (Bardeli et al. 2010).

Autonomous recording units (ARU) have been used to detect a variety of seabird species (Buxton and Jones 2012, Oppel et al. 2014, Cragg et al. 2016). However, the application of ARUs for the study of seabirds has been limited to documenting seabird presence, or for indices of abundance through metrics such as the number of calls recorded. (e.g. Borker et al. 2014). However, this correlation cannot be applied to other species without direct observations of call rates in colonies of known size. In fact, it is unlikely that the same call frequency and colony size relationship holds true across all seabird taxa as avian vocal behavior is dependent on many factors including conspecific density (Penteriani et al. 2002, Penteriani 2003).

In acoustic surveys, animal density determination methods have usually involved either localization through sensor arrays using the time-of-arrival differences, based upon acoustic multipath propagation effects, or using propagation models (Mellinger et al. 2007). To apply either method for bird surveys using fixed passive acoustic independent sensors, information about the acoustic environment and the detection distance of the equipment, along with

information about the calling rate of the animals is necessary to determine density (Hobson et al. 2002, Celis-Murillo et al. 2009, Marques et al. 2013).

Acoustic behavior, particularly the call rate of the focal species, is important for determining the number of birds present within the study area (Buckland et al. 2001). Little work has been conducted evaluating the call rates of seabird species, especially nocturnal petrel and shearwater species (but see Ryan 1988). Passive acoustic studies of seabirds are increasingly using Song Meter acoustic sensors (Wildlife Acoustics Inc.) due to their affordability, compact size, and ease of use. Song Meter sensors have been used to determine the presence and distribution of Marbled murrelet (*Brachyramphus marmoratus*) and Ancient murrelet (*Synthliboramphus antiquus*) in Alaska, Newell's shearwater (*Puffinus newelli*) in Hawai'i, and Ashy storm-petrel (*Oceanodroma homochroa*) in California (Buxton and Jones 2012, Cragg et al. 2015, Harvey et al. 2016). Despite the widespread use of acoustic sensors to determine the presence and distribution of seabirds, only a single study has been conducted to determine the difference in detection probability in habitats of different physical structure and forest canopy openness (Cragg et al. 2015).

For seabird populations to be managed better, tools and techniques need to be developed and standardized to make monitoring and population size determination easier. A better understanding of the technical capability of these acoustic sensors and the propagation properties of seabird calls will allow for these techniques to be used in a quantitative, rather than qualitative manner. Currently, a lack of understanding about the ways in which seabird calls propagate within their terrestrial environments in addition to an understanding of the vocal behavior of the target species are the main roadblocks to advancing the use of these tools

for the determination of animal densities. To address this lack of knowledge about the detection ability of commonly used ARUs, the goal of this study is to investigate the differences in detection probability for Song Meter sensors under different habitat and environmental conditions in a remote island context. To address this goal, I will seek to address the following questions: 1) What is the detection range of Song Meter acoustic sensors in different habitat types; and 2) How do seabird calls attenuate over distance under different habitat and environmental conditions.

Methods

Study Site

To address my research questions I chose the Islands of Ta‘ū and Tutuila, American Samoa, located in the South Pacific Ocean (Figure 1). American Samoa is an unincorporated territory of the United States, and the island of Ta‘ū is located in the Manu‘a group of islands, to the east of Tutuila, the main island of American Samoa. Ta‘ū is a high volcanic island with a forested montane summit region that provides important breeding habitat for Tahiti petrel (*Pseudobulweria rostrata*), Tropical shearwater (*Puffinus bailloni*), and Herald petrel (*Pterodroma heraldica*; Amerson et al. 1982, Pyle et al. 1990, O’Connor and Rauzon 2004). This study was conducted within the National Park of American Samoa in the montane and summit scrub region of Ta‘ū and Tutuila. The montane forest and summit scrub habitats on Ta‘ū are characterized by cool temperatures (6° C less than sea level) and high rainfall between approximately 4,500 – 9,000 mm y^{-1}, of mostly orthographic precipitation (Whistler 1992). The forest canopy is shorter than in lowland forest with most trees < 18 m. In addition, the canopy

is broken, with dense ground cover underneath (Whistler 1992). The summit scrub habitat is similar to montane forest in flora, however high winds and moisture keep the vegetation in a constant state of disturbance in which understory species dominate (Whistler 1992). The dense ground cover is dominated by *Freycinetia storckii*, a coarse climbing vine, interspersed with ground ferns and flowering plants (Whistler 1992).

Detection Range Experiments

To determine the detection ranges of Song Meter SM2 and Song Meter SM4 autonomous acoustic sensors, experiments were performed on Ta‘ū on August 6 and 8, 2016, and on Tutuila on July 26, 2016. Detection range was estimated by attaching Song Meters to a tripod at a height of 1.5 m and placed at sites determined to have either closed (> 25% canopy closure) or open (< 25% canopy closure) canopy habitat types (Table 1). The Song Meter SM2 sensor was set with single (mono) channel recording in all experiments. In a subset of the experiments I paired the Song Meter SM4 sensor with an older SM2 sensor. Song Meter SM4 sensors have many of advantages for field use over older SM2 sensors, including better battery performance and lighter weight. The main acoustic recording difference between the two sensors is microphone performance. The Song Meter SM4 sensor uses microphones with a sensitivity of -28 ± 3 dB (0 dB = 1V/pa@1 Hz) while the SM2 sensor microphones have a sensitivity of -36 ± 4 dB (0 dB = 1V/pa@1 Hz). The SM4 sensors were set with a gain of 16 dB, and the SM2 sensors were set with a gain of 48 dB. Sample rate for both sensors was set at 22,050 Hz. This pairing allowed for a comparison of the performance of the two types of sensors under standard setting that allowed for optimal recording of seabird calls (Table 1).

Detection range was determined by setting the Song Meter sensors to continuously record while I played a pre-recorded playback track at 1 m from the sensor, then at increments of 10 m from 10 - 100 m from the sensor. The playback track consisted of different seabird calls, with each call repeated five times. These were two versions of the Tahiti petrel call, a Herald petrel call, and a Tropical shearwater call (Figure 2). Tahiti petrels have one of the more varied vocal repertoires of the Procellariiformes (Rauzon and Rudd 2014) so I included two different vocalizations of Tahiti petrel in the study. The first Tahiti petrel call (Figure 2A) is a flight call with an initial up-slurred whistle with harmonics between 1,000 and 7,000 Hz. The whistle is followed by a low frequency moan with peak energy around 500 Hz. While this flight call was recorded from a petrel in motion, the call was played back from a static location thus not completely mimicking the characteristics of a true flight call. The second Tahiti petrel call (Figure 2B) is a ground call which contains the whistle with harmonics, followed by an elongated whistle at approximately 4,000 Hz, ending with a descending moan. The Herald petrel call (Figure 2C) is a typical *"ti-ti"* call consisting of repeated staccato notes with peak energy around 2,500 – 4,500 Hz. The Tropical shearwater call (Figure 2D) consists of a repeating pattern of broadband signal with a fundamental frequency around 1,500 Hz and a short whistle that rises from 1,500 – 2,000 Hz and back again to 1,500 Hz. All seabird calls used were previously recorded within the colony nesting area on Ta‘ū.

In addition, single frequency tones lasting 0.5 seconds were played in sequence at 500, 1,000, 2,000, 3,000, 4,000, 5,000, 6,000, and 7,000 Hz. This standardized frequency sequence was chosen to cover the range of frequencies that the seabird calls naturally covered, and was repeated five times. At each distance the entire playback track was replicated three times. At

each distance between 1 – 100 m, the maximum and average wind speed over 30 seconds was recorded at a height of 2 m using a hand-held Kestrel 2000 wind meter (Nielsen Kellerman). Wind speed values were averaged over the entire distance range from 1 – 100 m for each individual experiment as there was no significant difference in the wind speed values within each experiment. The playback source was upwind of the ARU in all experiments. Average wind speeds above 8 km h^{-1} were classified as high wind conditions and those under 8 km h^{-1} classified as low wind conditions. Additionally, temperature at the ARU was measured throughout each experiment.

The playback track was played with a 5 w portable speaker (Gshine) and Mp3 player (Apple Inc. iPod) at a height of 1.5 m above the ground and directed towards the ARU. The playback track was played at an average maximum of 76.5 dB (± 1.4 S.D.) for the seabird calls and 85.5 dB (± 2.5 S.D.) for the tone sequence measured at 1 m (reference sound pressure 20 μPa). Playback at 1 m was measured using a Pyle PSPL25 hand held sound level meter (Pyle Audio Inc.). This playback level was chosen to be within a range similar to the measured call dB levels of other Procellariiformes seabirds (Curé et al. 2011). The performance of the portable 5 w speaker was determined by measuring the difference in dB output at frequency intervals of 500 Hz at a range from 500 to 8,000 Hz. The difference in dB for each frequency from the maximum dB measured was used to explain frequency specific differences within the field recordings (Figure 3).

Average canopy closure was determined using a convex spherical crown densiometer (Forestry Suppliers Inc.) with the overhead percentage of canopy cover averaged over four measurements in the cardinal directions. A canopy closure measurement was made at the site

of the sensor and at each playback location. Canopy closure was then averaged over the entire experimental area to determine open or closed canopy conditions. The canopy type (open/closed) was determined to be open using a threshold of < 25% cover. Average canopy closure at the High Lata site was 24.8% with an average canopy height of 2.7 m. Average canopy closure at the Low Lata site was 37.4% with an average canopy height of 5.2 m. Finally, average canopy closure at the Alava site was 56.6% with an average canopy height of 9 m (Table 1). A simple rain gauge was deployed next to the acoustic sensor and the amount of precipitation (mm) determined over the 60 min of each experiment, however there was no appreciable precipitation during any of the field experiments. Each experiment lasted for approximately 60 minutes and experiment starting times ranged between 11:52 and 16:14 (Table 1).

Call Recognition and Analysis

Recordings were analyzed using both manual and automated approaches. Manually analyzed data were reviewed both visually and aurally in Adobe Audition (Adobe Inc.) and the number of each call type detected at each distance was counted. Each detected call was saved as a separate file and the Signal to Noise Ratio (SNR) in dB calculated.

Next, I analyzed the recordings using the Kaleidoscope automated cluster analysis tool (Wildlife Acoustics Inc.), which uses a machine learning approach to detect and classify all of the signals within a recording into user determined clusters. The classifier then incorporates user validation to identify the clusters to the correct species of interest (Heist 2014, Machado et al. 2017). This identification process was completed on a subset of data, in this case, a single

experimental run from the field. The calls classified within each cluster are sorted by their non-metric distance from the cluster center, essentially a measure of how closely a given call matches the call representative of the cluster. Clusters which represented Tahiti petrel flight call, Tahiti petrel ground call, Herald petrel, and Tropical shearwater were manually identified. The individual frequencies within the standardized frequency sequence could not be separated by the automated detection method. Instead, they were detected as a block containing one or more frequency bands. Only those clusters where the calls were correct within 80% of the cluster centroid were classified. Finally, these training data were used as the basis for the automated cluster analyzer to determine calls throughout the rest of the field recordings. Each recording was split into sections that represented each distinct distance from the sensor. In this fashion, the output from the analyzer was able to identify the number of calls within each distance for each species that was detected.

Statistical Analyses

The Signal to Noise Ratio (SNR) was calculated as:

$$\mathrm{SNR} = \left(\frac{A_{\mathrm{signal}}}{A_{\mathrm{noise}}}\right)^2$$

where A_{signal} is the averaged amplitude of the signals and A_{noise} is the averaged amplitude of the background noise as measured prior to the playback track at each distance. The number and SNR of calls at each distance were analyzed for differences between the three condition groups of: 1) high wind, open canopy cover; 2) low wind, open canopy cover; and, 3) low wind, closed canopy cover. Between group differences in mean percent calls detected and SNR were

determined using non-parametric Kruskal-Wallis tests. Additional tests compared the detection rate from visual and aural data processing with the automated model processing restricted to data collected from SM4 sensors. To determine the effect of the type of data processing method on detectability, the analysis was restricted to the SM4 data with all low wind conditions combined. To examine the effect of sensor type on detectability (SM2 vs. SM4), analysis was restricted to data from low wind, open canopy conditions and analyzed manually to prevent high wind conditions confounding the results. All statistical tests were performed using SPSS 24 (IBM Corp.). Significance limits for Kruskal-Wallis tests were set at $P \leq 0.05$.

Results

Call Detectability

Environmental conditions

Visual and aural (manual) inspection of the Song Meter SM2 and SM4 audio streams indicated a decrease in detectability with distance for all species' calls and tone frequencies (Figure 4, Figure 5). There were significant differences in the detectability of calls for all species based on the wind speed and canopy cover (Table 2). In high wind environments, both types of Tahiti petrel call were undetectable after 50 m. The detection rate of the Tahiti petrel flight call fell under 50% by 40 m and the detection rate of the Tahiti petrel ground call fell under 50% by 50 m. Herald petrel and Tropical shearwater calls were undetectable at 40 m and detection rate fell under 50% by 20 m (Figure 4). Within low wind, open canopy environments, species calls exhibited steep drop offs in detectability between 40 and 60 m and detection rates fell under

50% by 60 m (Figure 4). In low wind, closed canopy environments, all species calls showed an initial decrease in detectability, but then showed greater detectability relative to open canopy environments at distances over 60 m. Detection rates fell under 50% between 60 and 90 m (Figure 4).

Within low wind, open canopy environments, the tone frequencies showed a similar steep drop off in detectability with every frequency except 500 Hz undetectable at 80 m and detection rates fell below 50% between 70 and 80 m (Figure 5). Low wind, closed canopy environments showed similar patterns for all tone frequencies, with an initial drop off in detectability, and then higher detectability relative to open canopy environments above 60 m. Detection rates for all frequencies other than 1,000 Hz fell below 50% at 90 to 100 m (Figure 5). High wind, open canopy environments showed a trend that differed among frequencies. At 500 and 1000 Hz, there was a rapid decrease in detectability with the tones being undetectable at 40 m and detection rates falling below 50% by 10 m (Figure 5). However, as frequency increased, the rate of detectability decrease lessened. There were significant differences in detectability between the wind and canopy groups for frequencies between 500 and 5,000 Hz, but not for 6,000 or 7,000 Hz (Table 2).

A decrease in detectability with distance for all species calls and tone frequencies was also observed in the Kaleidoscope automated cluster analysis of the Song Meter SM4 audio streams (Figure 6). There were significant differences in the detectability of calls for all species and tones, except Herald petrel, based on the wind speed and canopy cover (Table 3). In high wind environments, both Tahiti petrel call types and Herald petrel calls were undetectable at 20 m. Tropical shearwater calls were detected at low proportions out to 100 m (Figure 6).

Detection rates of both Tahiti petrel calls and tones dropped under 50% by 10 m and detection rates for Herald petrel and Tropical shearwater calls were never above 50%.

Within low wind, open canopy environments, species calls and tones exhibited steep drop offs in detectability between 20 and 70 m. Detection rates fell under 50% by 10 m for Tropical shearwater, by 30 m for Tahiti petrel flight call and Herald petrel, and by 60 to 70 m for the Tahiti petrel ground call and for tones (Figure 6). In low wind, closed canopy environments, both Tahiti petrel calls were detectable out to 90 m and tones were detectable out to 100 m. Herald petrel and Tropical shearwater calls showed an initial sharp decrease in detectability, becoming undetectable by 20 m and 10 m respectively. Detectability fell under 50% at 90 m for tones, 40 m for the alternate Tahiti petrel call, 20 m for Tahiti petrel and Herald petrel, and 10 m for Tropical shearwater (Figure 5).

Data processing method

There were significant differences between the detectability of the two methods for the Tahiti petrel flight call ($\chi^2 = 9.786$, df = 1, $P = 0.002$), Herald petrel ($\chi^2 = 10.232$, df = 1, $P = 0.001$), Tropical shearwater ($\chi^2 = 18.838$, df = 1, $P < 0.001$), and the combined frequencies ($\chi^2 = 44.177$, df = 1, $P < 0.001$, Figure 7). In every case, manual data processing outperformed automated processing at every distance from the sensor (Figure 7). Detection rate dropped under 50% for Tahiti petrel and Herald petrel at 20 m for the automated method, and 60 m for the manual method. Detection rate dropped under 50% for Tropical shearwater at 10 m for the automated method, and 40 m for the manual method. Detection rate dropped under 50% for tones at 70 m for the automated method, and was still above 50% at 100 m for the manual

method. The Tahiti petrel ground call had the closest performance between automated and manual processing, with detection rate dropping under 50% at 60 m and 70 m respectively (Figure 7).

Sensor type

For Song Meter SM4 sensors there was a drop off in detectability for both Tahiti petrel calls after 60 m (Figure 8). Detection rate fell under 50% for the Tahiti petrel flight call by 80 m, and for the ground call by 100 m (Figure 8). Herald petrel calls dropped off after 50 m, with detection rate falling under 50% by 70 m. Tropical shearwater call detection dropped off after 30 m with detection rates falling under 50% by 40 m (Figure 8). Detectability for SM2 sensors dropped off for all species after 10 m. Detection rates fell under 50% by 40 m for the Tahiti petrel flight call, Herald petrel, and Tropical shearwater. The Tahiti petrel ground call detection rate fell under 50% by 70 m (Figure 8). There was a significant difference in detectability between the sensors for both Tahiti petrel flight calls ($\chi^2 = 4.347$, df = 1, $P = 0.037$) and Tahiti petrel ground calls ($\chi^2 = 5.145$, df = 1, $P = 0.023$), with detectability being higher for the SM4 sensors (Table 4).

Tones were detected by the SM4 units all the way out to 100 m and detection rates did not drop off until after 80 – 90 m for all frequencies except 1,000, 2,000, and 3,000 Hz. These frequencies exhibited drop offs in detection rates after 60 – 70 m (Figure 9). Detection rates did not fall under 50% by 100 m for 500, 4,000, 5,000, and 6,000 Hz. Detection rate fell under 50% for 1,000 Hz by 80 m (Figure 9). Detection rates fell under 50% by 30 to 40 m for all frequencies expect 5,000 Hz which fell under 50% by 80 m (Figure 9). Overall detection rates for SM2

sensors were much lower. Initial drop offs in detection rates occurred at 10 – 20 m. Some mid-range and low frequencies were detected out to 100 m (Figure 9). There was a significant difference in detection rate between sensor types for all frequencies with detection rate being higher for SM4 sensors for all frequencies (Table 4).

Signal to Noise Ratio of Detected Calls

The SNR of all detected calls showed high SNR close to the sensor which rapidly declined over 20 m (Figure 10). SNR in high wind conditions dropped to low levels at 10 m from the sensor for all species. SNR was higher for low wind conditions, but variable with distance (Figure 10). There were significant differences between wind and canopy conditions for the Tahiti petrel flight call ($\chi^2 = 9.975$, df = 2, $P = 0.007$) and the Tahiti petrel ground call ($\chi^2 = 9.090$, df = 2, $P = 0.011$). There was no significant difference between groups for the Herald petrel or Tropical shearwater calls (Table 5).

The SNR of the tones showed a similar pattern with higher SNR close to the sensor and rapidly declining at any distance from the sensor (Figure 11). High wind and low wind closed conditions were similar, with SNR reaching low values by 20 m. Low wind, open conditions exhibited high SNR close to the sensor then dropped off and became variable after 20 m (Figure 11). There were significant differences between groups for all frequencies with low wind, open canopy conditions showing higher SNR than low wind, closed canopy, and high wind conditions (Table 5).

I evaluated the sensitivity of the Gshine portable speaker used in this study by measuring the differences in dB at frequencies between 500 and 8,000 Hz (Figure 3). Speaker

sensitivity was generally flat between 2,500 and 8,000 Hz; however, speaker performance underperformed the calibrated level at 1,500 and 2,000 Hz by 11 dB and 13 dB respectively (Figure 3).

Discussion

My results show that environmental and habitat conditions can have a large impact on the effective sampling range of remote acoustic sensors. Variation in canopy cover and wind speed caused significant differences in detection distances of seabird calls and pure tones up to 6,000 Hz. Low wind conditions resulted in higher levels of detectability. Detection range was significantly greater in low wind conditions than high wind conditions, reflecting the large acoustic masking effect that wind noise has on acoustic recording equipment. Call detection and sound level decreased with distance from the recording device, as expected from spherical spreading and pattern loss due to scattering (Bradbury and Vehrencamp 1998). The different wind conditions and canopy structure had an impact on the detectability of calls and the SNR of the calls detected. In high wind conditions, lower frequencies decreased in detectability much faster than higher frequencies (Figure 5). This decrease in detectability at the low frequencies of 500 and 1,000 Hz can likely be attributed to the large increase in low frequency noise caused by windy conditions (Berglund et al. 1996).

The difference between detectability in open versus closed canopy environments is expected because increased forest cover results in increased acoustic scattering (Richards and Wiley 1980). It is possible that high wind sound shadowing, where sound waves fail to propagate in open environments, may contribute to the decrease in detectability at distances

over 60 m. Alternatively, sound reflection off the dense tree canopy may aid detectability at larger distances in closed canopy environments (Delany 1977). The detectability of the seabird calls also declined in high wind conditions. Of note is that the Tahiti petrel ground call exhibited higher detectability in high wind compared to the other species calls, and that overall detectability was lowest for Tropical shearwater calls. This lower detectability could be due to these calls lacking prominent harmonics and clear tonal whistles within the call (Figure 4).

When using ARUs, both the environmental and habitat conditions should be considered in the design of the study. If ARUs are to be used in windy or otherwise noisy environments then sensors should be placed closer together, and more sensors would be required to effectively survey a given area. Attention should be paid to environmental and habitat conditions when comparing the results of studies using ARUs covering multiple locations.

In the future, methods should be developed that will allow ARUs to be used to determine the density of animals. These density determinations require two things: 1) known call rate of the species; and, 2) known detection range of the ARU. While the determination of density has been achieved in ornithological studies using sensor arrays over small areas, additional increases in technological capacity are needed to make calculating densities practical using a collection of single ARUs. Understanding the calling rate of the species being studied is vital to converting the recorded total number of calls, or calls per minute into a density of animals. A further consideration is that when environmental conditions change, the effective detection distance of the ARU also changes. If small wind and rain measuring devices were to be deployed along with ARUs in the field, it would yield environmental data that could be correlated with the results of the acoustic detections allowing for correction factors to be

applied to the data according to the changing detection ranges of the ARUs as environmental conditions change.

Environmental conditions, habitat structure, and the acoustic composition of the calls of the study species impact the detection ability of the ARU. Furthermore, detectability differs between manual screening of data and automated computer driven screening. As expected, the automated cluster analysis call processing method detected far fewer calls than did manual call processing. The automated cluster analysis was better at detecting both versions of the Tahiti petrel call and the generated tones than at detecting Herald petrel and Tropical shearwater calls. However, detectability rates from the automated cluster analysis were still lower than those from manual processing, agreeing with research from the marine mammal field comparing false positive detection rate for different data processing methods (Mellinger 2004). This variation in detectability indicates that the characteristics of the call are important to determine the efficacy of automated models to make detections. Specifically, calls with clear tonal features in mid-range frequencies with harmonics were detected more often than were calls with short, repeated, broad frequency characteristics, both manually and with the automated analysis. However, it is important to note that the speaker sensitivity significantly underperformed at 1,500 and 2,000 Hz. This decreased performance may have negatively impacted detection at these frequencies, however the neighboring frequencies of 500 and 3,000 Hz also indicated a decrease in detection, particularly under high wind conditions. Automated screening of data is more practical given the large quantities of data from remote acoustic monitoring studies, yet this difference in detection ability should be taken into account

in studies in the future through the quantification of false positive and false negative detection rates.

The combined effective functional detection distance of Song Meter SM4 sensors in this tropical montane habitat was approximately 40 to 70 m, depending on the species and environmental conditions. The significant time requirements for manual processing means that this method is unrealistic when large amounts of data are being generated, as occurs in long-term projects, and those projects which cover multiple sites (Mellinger et al. 2007). The effective functional detection distance of SM4 sensors was significantly lower for the Tahiti petrel flight call, Herald petrel, and Tropical shearwater call at approximately 20 m. The difference between the methods of analysis for the calls other than the Tahiti petrel ground call indicates that additional work is required to develop automated methods of analysis that can detect calls which cover a wide frequency range and lack distinct tones.

The Song Meter SM4 sensors clearly outperformed the SM2 sensors with respect to detection rate (Figure 8). This difference in the detection rate is to be expected given the newer technology and capability of the SM4 sensors, and should be considered when planning future research. To understand the differences in detectability between the sensors, projects should pair deployments of both SM2 and SM4 sensors so that the differences in detectability can be ground-truthed and correction factors can be created to standardize the results of monitoring studies. Even with this improved function, the detection range of SM4 sensors in this study was still less than 100 m, even under extremely good environmental and weather conditions.

The functional detection distance of the older Song Meter SM2 sensors was in line with the measured detection distance of these sensors for other species and habitats. In forested

habitats, Marbled murrelets were detectable out to 60 m (Cragg et al. 2015). Additionally, the effective detection distance of boreal song birds was found to be 50 m (Venier et al. 2012). The general effective detection distance of 40 to 70 m translates to an area surveyed to 0.5 ha to 1.53 ha depending on the species and assuming omni-directional propagation. The effective surveyed area is going to be extremely different depending on the species and conditions encountered. Wind variability can significantly change the ability to detect the call, indicating that while there is a clear difference in the detection range of the sensors with respect to wind speed, even during good or optimal conditions, the range will be variable within short term time scales. For acoustic sensors to be effectively used to determine density, there must be an understanding of how the detection range varies over short term time scales.

This study has provided increased understanding of how different species of Procellariiform seabirds can be detected using ARUs under field conditions in montane colonies. These conditions can be highly variable and may often result in significant compromises in the ability to detect seabird calls and the distances they can be detected at. Given the increasing use of ARUs to study cryptic and difficult to access seabird populations, it is important to collect data on the habitat structure and real time environmental data in order to understand how detection distances will vary over time.

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Tables

Table 2.1. Summary of location, environmental details, and type of automated recording unit (ARU) used for the field experiments.

ID	Date	Time	Location	Sensor	# channels	Average Canopy Cover (%)	Average Canopy Height (m)	Wind Max (km h^{-1})	Wind Average (km h^{-1})	Average Temperature (°C)
A1	7/26/16	11:52	Alava	SM4	1	56.6	9	1.8	1.0	30.5
L1	8/1/16	14:45	Lata High	SM4	2	24.8	2.7	2.9	2.4	29.75
L2	8/6/16	13:58	Lata High	SM4, SM2+	2	24.8	2.7	13.5	9.8	25.0
L3	8/6/16	16:14	Lata Low	SM4, SM2+	2	37.4	5.2	2.1	1.1	24.25

Table 2.2. Mean percentage of calls detected for all species and tone frequencies. Detectability is split by the three treatment groups; low wind closed canopy, low wind open canopy, and high wind open canopy. Differences between groups are indicated by Kruskal-Wallis non-parametric tests, with significant differences noted in bold.

Species /	Mean % Calls Detected					
Frequency	low closed	low open	high open	χ^2	df	*P* value
TAPE 1	0.59 ± 0.06	0.53 ± 0.10	0.27 ± 0.05	12.416	2	**0.002**
TAPE 2	0.72 ± 0.05	0.57 ± 0.10	0.41 ± 0.07	9.832	2	**0.007**
HEPE	0.52 ± 0.06	0.52 ± 0.10	0.22 ± 0.05	9.402	2	**0.009**
TRSH	0.45 ± 0.06	0.48 ± 0.09	0.20 ± 0.05	7.489	2	**0.024**
500 Hz	0.74 ± 0.05	0.81 ± 0.06	0.14 ± 0.04	44.430	2	**<0.001**
1000 Hz	0.52 ± 0.06	0.63 ± 0.10	0.16 ± 0.04	19.746	2	**<0.001**
2000 Hz	0.66 ± 0.05	0.62 ± 0.10	0.24 ± 0.05	19.206	2	**<0.001**
3000 Hz	0.76 ± 0.04	0.61 ± 0.10	0.45 ± 0.06	14.371	2	**0.001**
4000 Hz	0.76 ± 0.05	0.61 ± 0.10	0.56 ± 0.05	6.869	2	**0.032**
5000 Hz	0.81 ± 0.04	0.63 ± 0.10	0.65 ± 0.05	9.130	2	**0.01**
6000 Hz	0.76 ± 0.05	0.62 ± 0.10	0.66 ± 0.05	3.405	2	0.182
7000 Hz	0.74 ± 0.05	0.61 ± 0.10	0.64 ± 0.05	3.051	2	0.217

Table 2.3. Mean percentage of calls detected for all species and tone frequencies played for calls detected from the automated cluster analysis. Detectability is split up by treatment group including; low wind closed canopy, low wind open canopy, and high wind open canopy. Differences between groups are indicated by Kruskal-Wallis non-parametric tests.

Species /	Mean % Calls Detected					
Frequency	low closed	low open	high open	χ^2	df	*P* value
TAPE 1	0.275 ± 0.06	0.321 ± 0.07	0.060 ± 0.04	12.958	2	**0.002**
TAPE 2	0.561 ± 0.09	0.527 ± 0.10	0.088 ± 0.06	19.065	2	**<0.001**
HEPE	0.155 ± 0.06	0.276 ± 0.09	0.042 ± 0.03	5.154	2	0.076
TRSH	0.058 ± 0.03	0.142 ± 0.07	0.142 ± 0.03	10.552	2	**0.005**
TONES	0.561 ± 0.04	0.467 ± 0.05	0.133 ± 0.04	22.379	2	**<0.001**

Table 2.4. Mean percentage of calls detected for all species and tone frequencies played for detections. Detectability is split up by sensor type including SM4 and SM2 sensors. Differences between groups are indicated by Kruskal-Wallis non-parametric tests.

Species /	Mean % Calls Detected				
Frequency	SM4	SM2	χ^2	df	*P* value
TAPE 1	0.66 ± 0.09	0.36 ± 0.09	4.347	1	**0.037**
TAPE 2	0.85 ± 0.05	0.50 ± 0.10	5.145	1	**0.023**
HEPE	0.57 ± 0.09	0.34 ± 0.09	2.352	1	0.125
TRSH	0.51 ± 0.09	0.29 ± 0.09	2.567	1	0.109
500 Hz	0.96 ± 0.01	0.59 ± 0.10	8.218	1	**0.004**
1000 Hz	0.72 ± 0.08	0.32 ± 0.09	9.387	1	**0.002**
2000 Hz	0.85 ± 0.05	0.34 ± 0.08	15.105	1	**<0.001**
3000 Hz	0.86 ± 0.04	0.55 ± 0.09	4.894	1	**0.027**
4000 Hz	0.93 ± 0.03	0.53 ± 0.10	6.893	1	**0.009**
5000 Hz	0.96 ± 0.02	0.57 ± 0.10	11.232	1	**0.001**
6000 Hz	0.93 ± 0.03	0.45 ± 0.09	13.610	1	**<0.001**
7000 Hz	0.91 ± 0.04	0.43 ± 0.09	13.937	1	**<0.001**

Table 2.5. Signal to Noise Ratio of all seabird calls and tones for manually detected calls. Detectability is split up by treatment group including: low wind closed canopy, low wind open canopy, and high wind open canopy. Differences between groups are indicated by Kruskal-Wallis non-parametric tests.

Species /	SNR dB of Calls Detected					
Frequency	low closed	low open	high open	χ^2	df	*P* value
TAPE 1	1.91 ± 0.49	37.10 ± 22.76	1.21 ± 0.50	9.975	2	**0.007**
TAPE 2	2.73 ± 0.50	67.88 ± 32.58	1.29 ± 0.43	9.090	2	**0.011**
HEPE	2.56 ± 0.55	47.64 ± 22.79	1.44 ± 1.43	3.640	2	0.162
TRSH	2.12 ± 0.58	17.21 ± 10.53	1.81 ± 0.79	1.833	2	0.4
500 Hz	1.16 ± 0.32	14.28 ± 5.86	1.60 ± 0.84	8.789	2	**0.012**
1000 Hz	1.45 ± 0.14	6.39 ± 2.32	1.05 ± 0.13	9.090	2	**0.011**
2000 Hz	2.73 ± 0.50	67.88 ± 32.58	1.29 ± 0.43	9.090	2	**0.011**
3000 Hz	1.48 ± 0.35	29.14 ± 21.14	0.89 ± 0.29	13.031	2	**0.001**
4000 Hz	1.88 ± 0.69	34.21 ± 20.88	0.81 ± 0.27	13.741	2	**0.001**
5000 Hz	1.74 ± 0.48	48.55 ± 24.57	0.80 ± 0.27	13.147	2	**0.001**
6000 Hz	1.37 ± 0.30	27.61 ± 11.24	0.76 ± 0.24	14.822	2	**0.001**
7000 Hz	2.14 ± 0.59	14.15 ± 7.40	0.86 ± 0.27	9.410	2	**0.009**

Figures

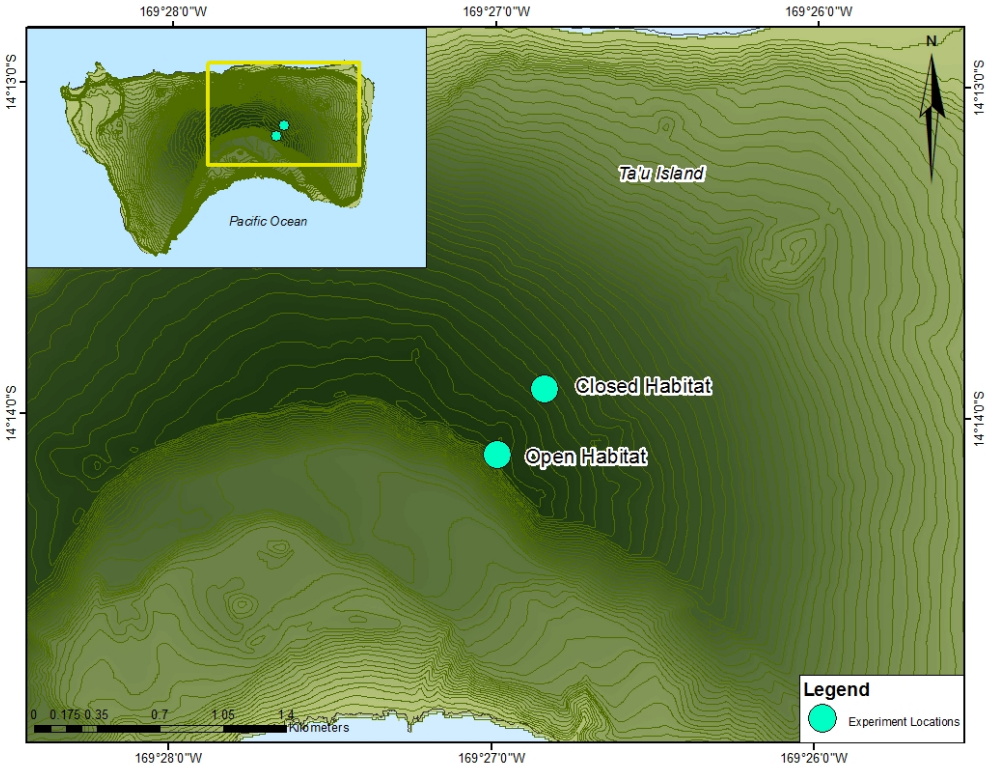

Figure 2.1. Locations of the closed canopy and open canopy experimental sites within the summit montane habitat on Ta‘ū, American Samoa.

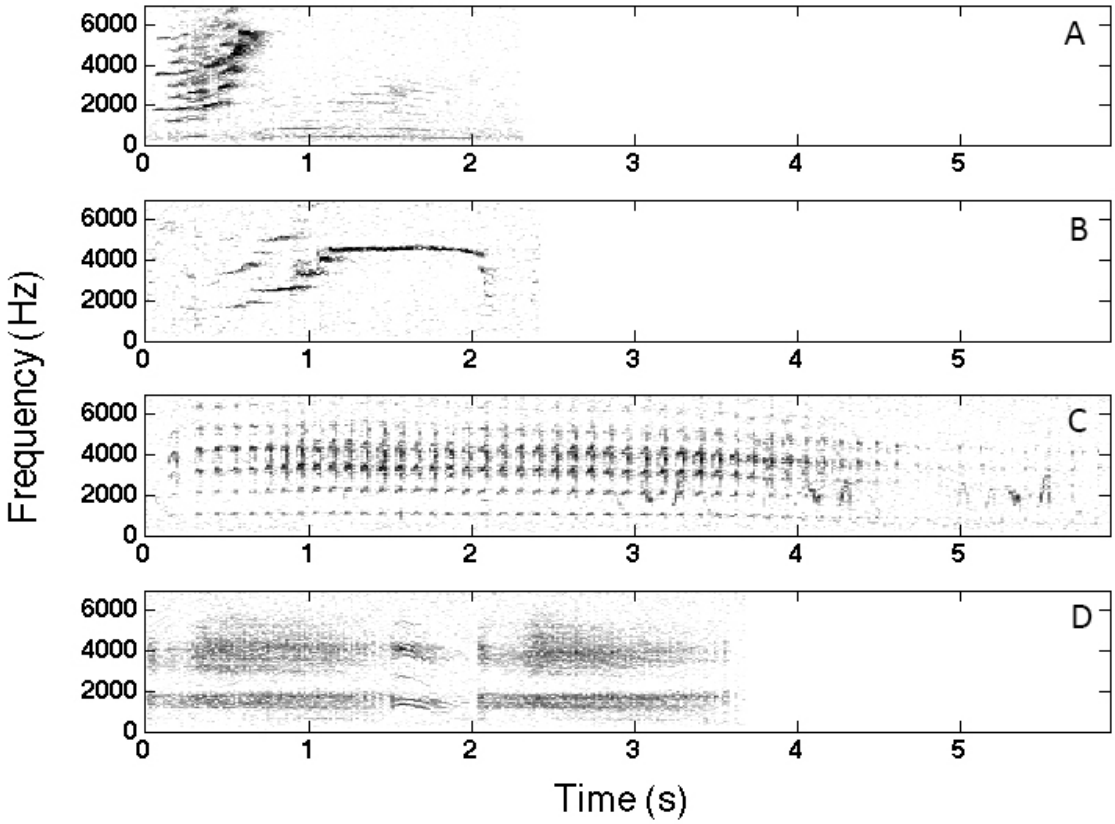

Figure 2.2. Spectrograms showing the flight call (A) and ground call (B) of the Tahiti petrel, the Herald petrel (C), and the Tropical shearwater (D). Calls were recorded in the summit colonies on Taʻū, American Samoa.

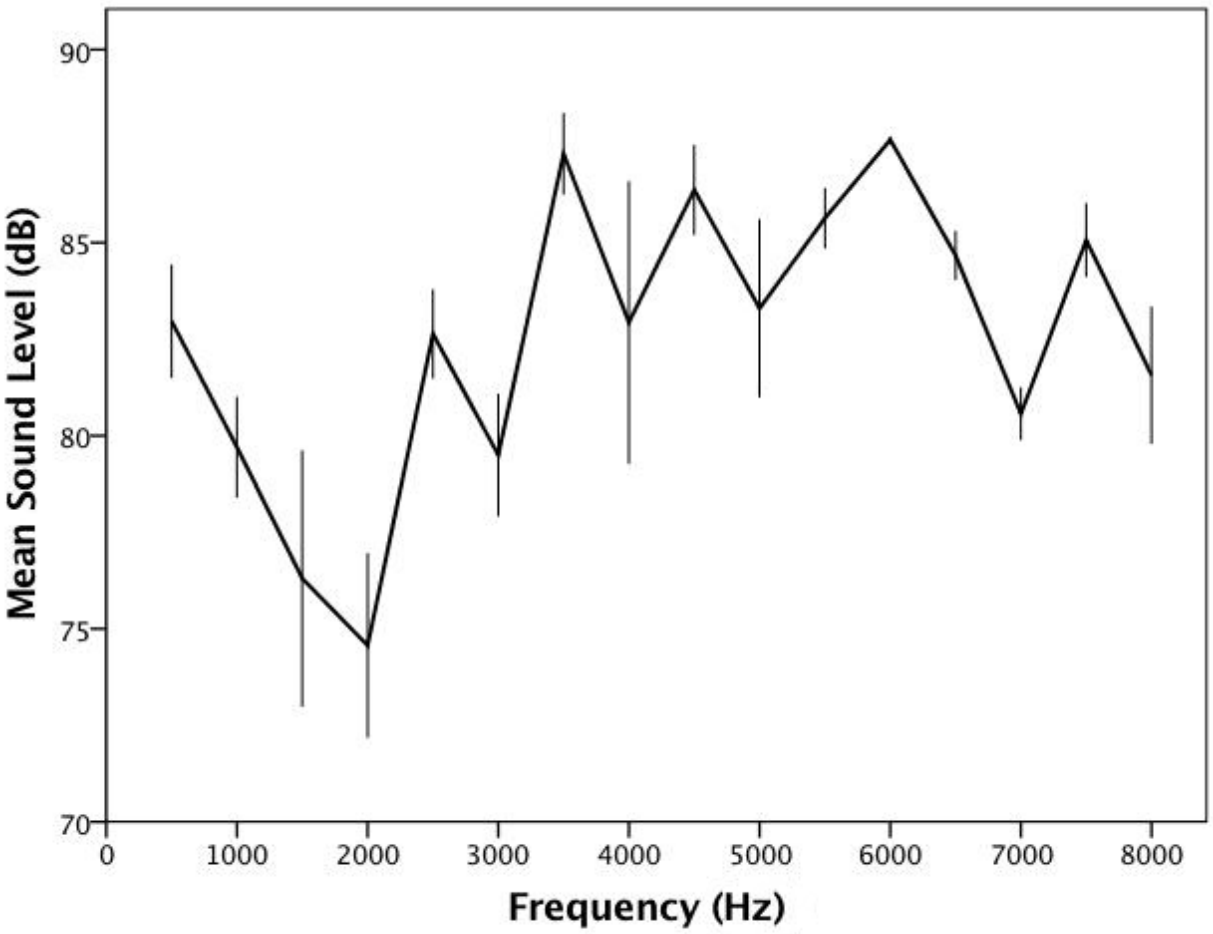

Figure 2.3. Mean (±S.E.) received sound pressure level (dB) at 1m (20 μPa) for frequencies between 500 and 8000 Hz. Frequencies were played using the Gshine portable speaker used in field experiments.

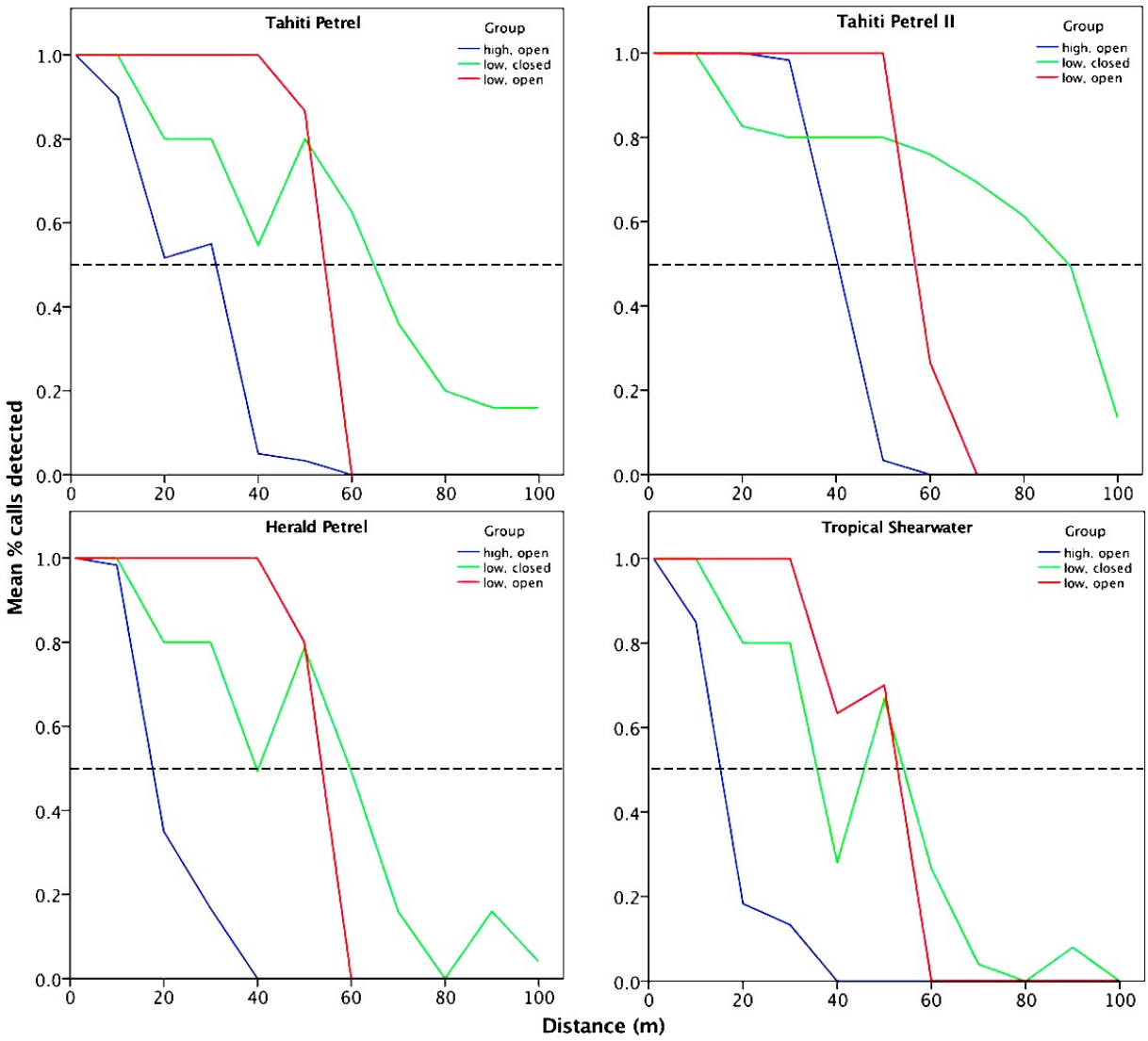

Figure 2.4. Mean percent calls detected with increasing distance from the recording sensor for four distinct calls from three species of Procellariiform seabirds. Shown within each panel is the difference in detectability from high wind, open canopy (blue), low wind, closed canopy (green), and low wind, open canopy (red).

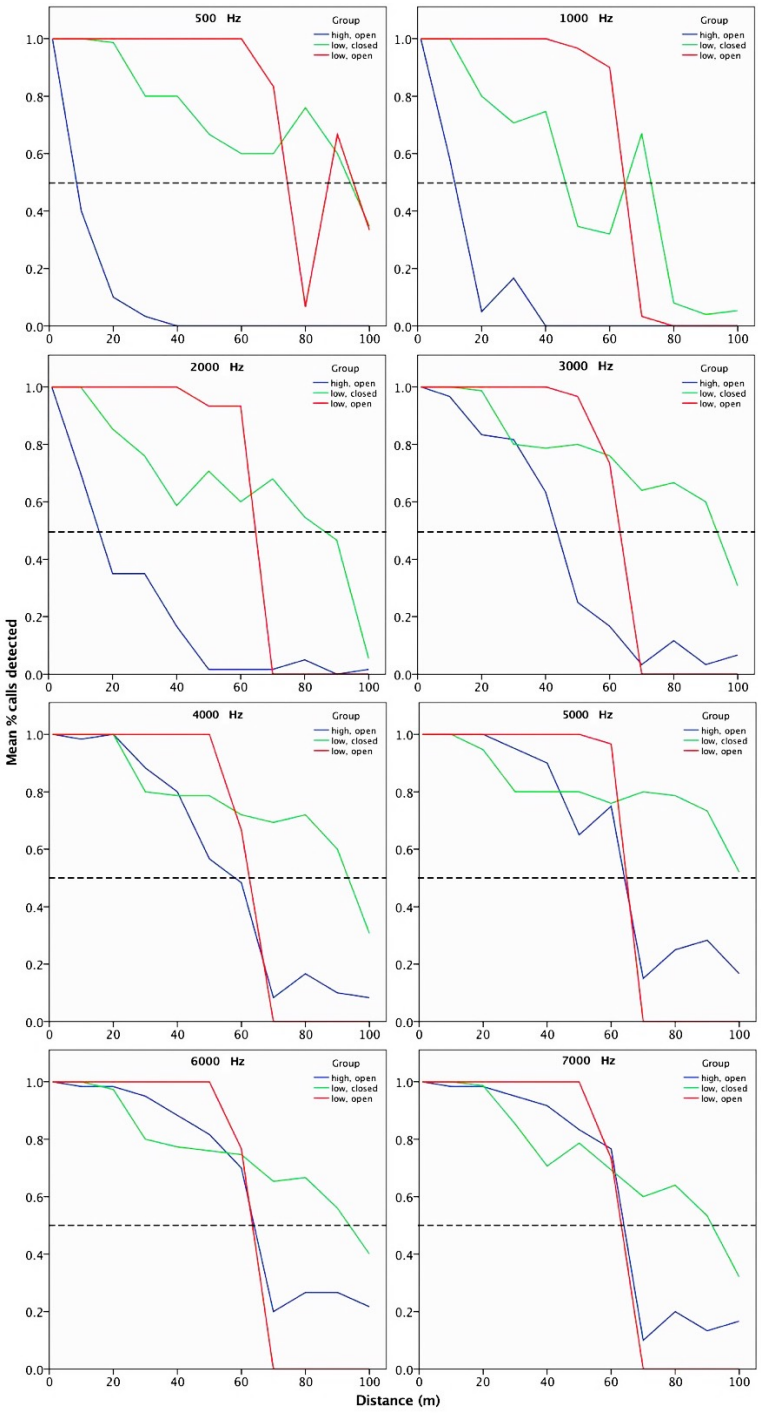

Figure 2.5. Mean percent tones detected with increasing distance from the recording sensor for 8 distinct tones from 500 to 7000 Hz. Shown within each panel is the difference in detectability from high wind, open canopy (blue), low wind, closed canopy (green), and low wind, open canopy (red).

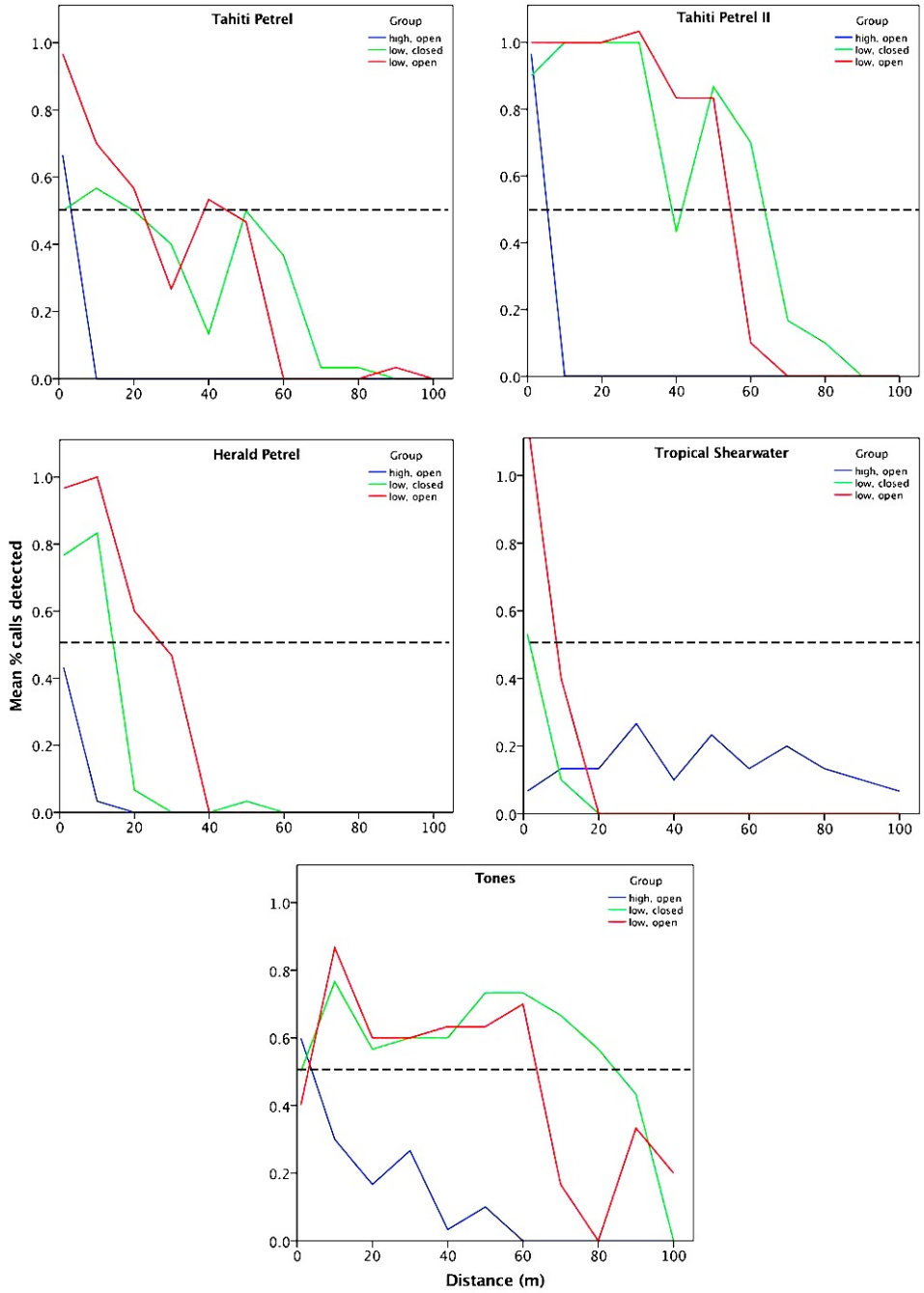

Figure 2.6. Mean percent calls detected with increasing distance from the recording sensor for four distinct calls from three species of Procellariiform seabirds and the combined tones from 500 – 7000 Hz. Calls were detected using Kaleidoscope cluster automated analysis. Shown within each panel is the difference in detectability from high wind, open canopy (blue), low wind, closed canopy (green), and low wind, open canopy (red).

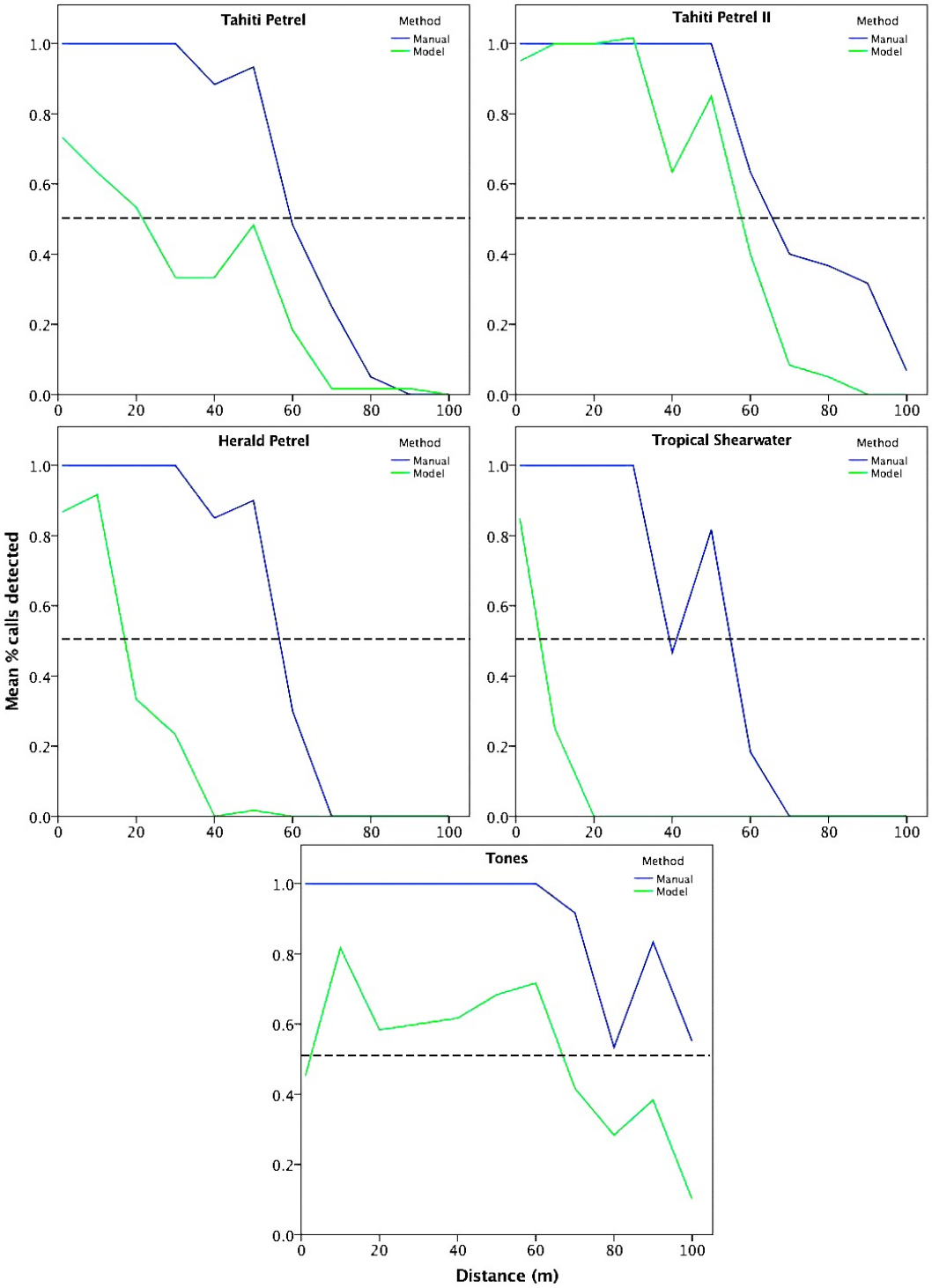

Figure 2.7. Mean percent calls detected over distance from the sensor for seabird calls and combined tones from 500 – 7000 Hz. Shown within panel are the two data processing methods including manual (blue) and automated cluster analysis (green).

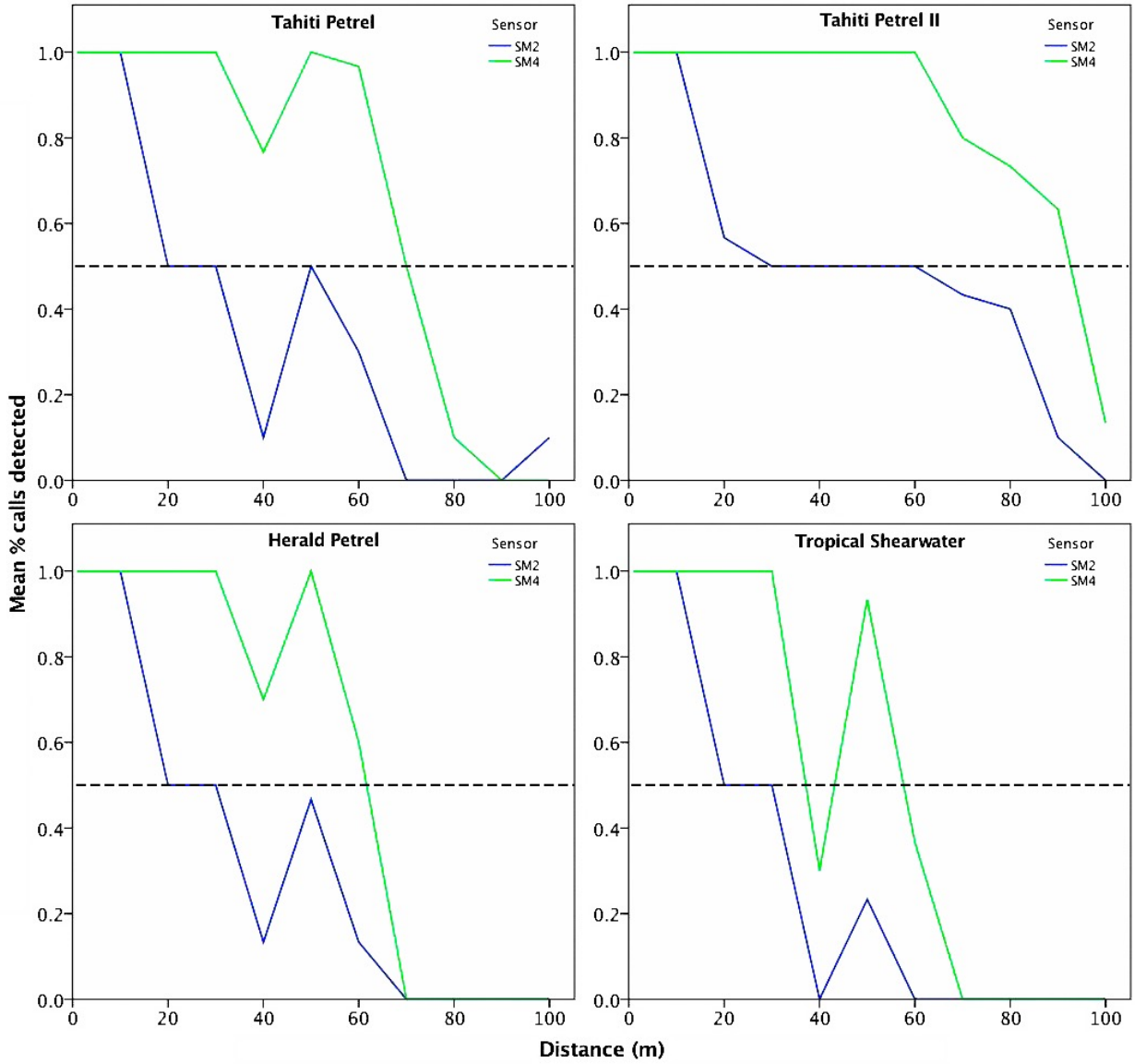

Figure 2.8. Mean percent calls detected over distance from the sensor for three species of Procellariiform seabirds. Shown in the panels are the differences between SM2 sensors (blue), and SM4 sensors (green).

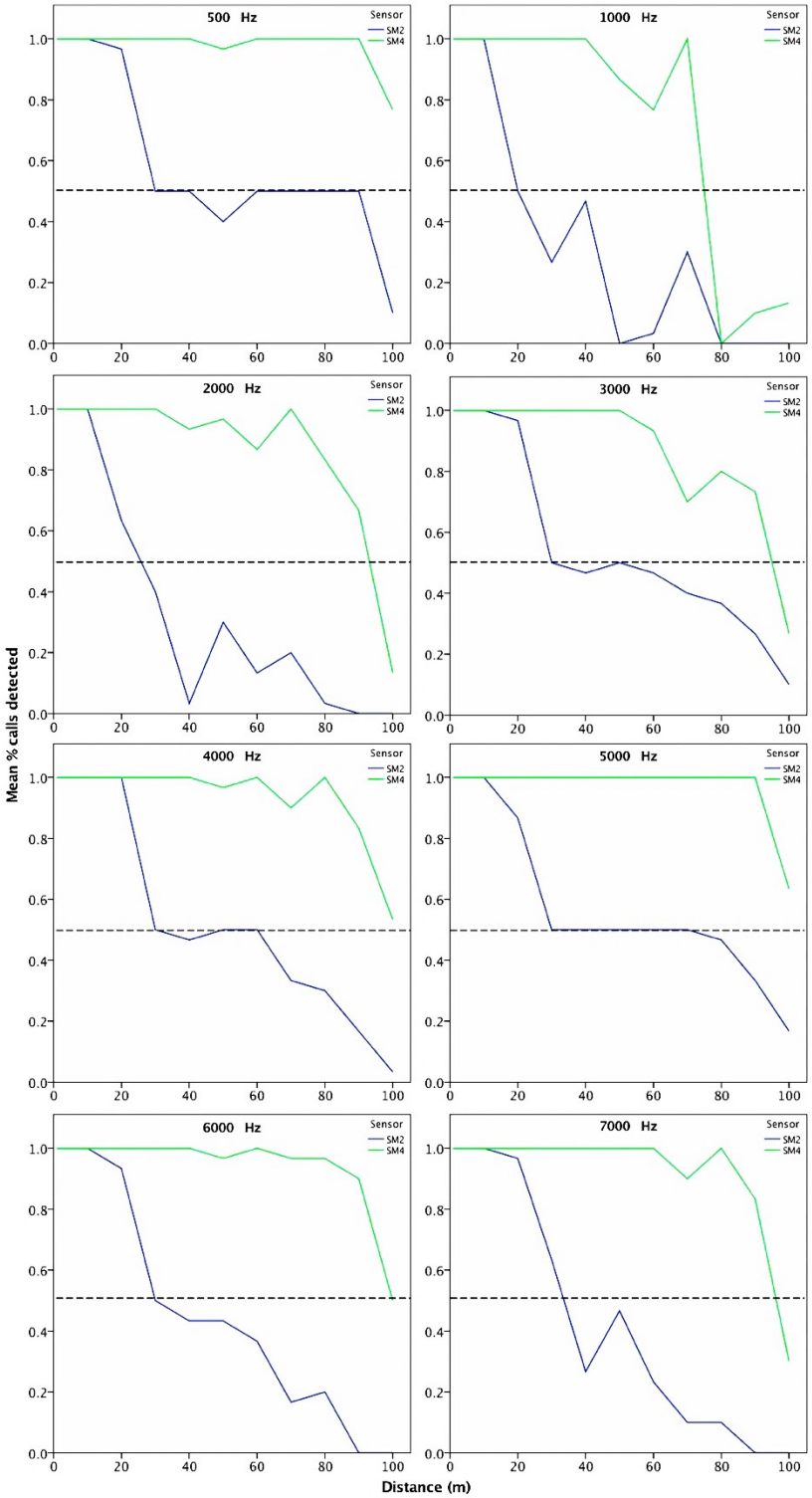

Figure 2.9. Mean percent calls detected over distance from the sensor for generated tones from 500 – 7000 Hz. Shown in the panels are the differences between SM2 sensors (blue), and SM4 sensors (green).

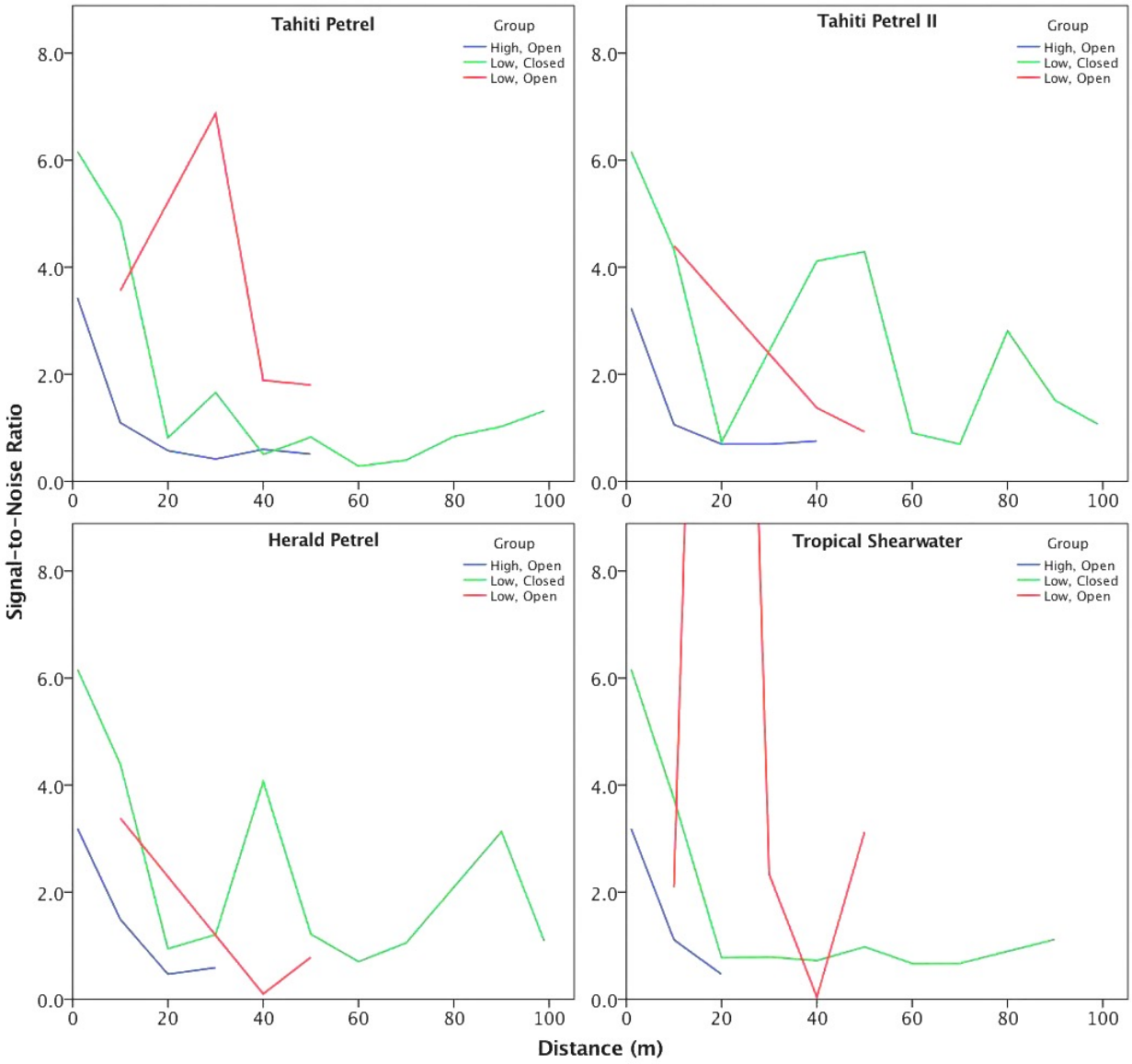

Figure 2.10. Signal to Noise Ratio (SNR) over distance from the sensor for detected calls from 3 species of Procellariiform seabirds. Shown within each panel is the difference in detectability from high wind, open canopy (blue), low wind, closed canopy (green), and low wind, open canopy (red).

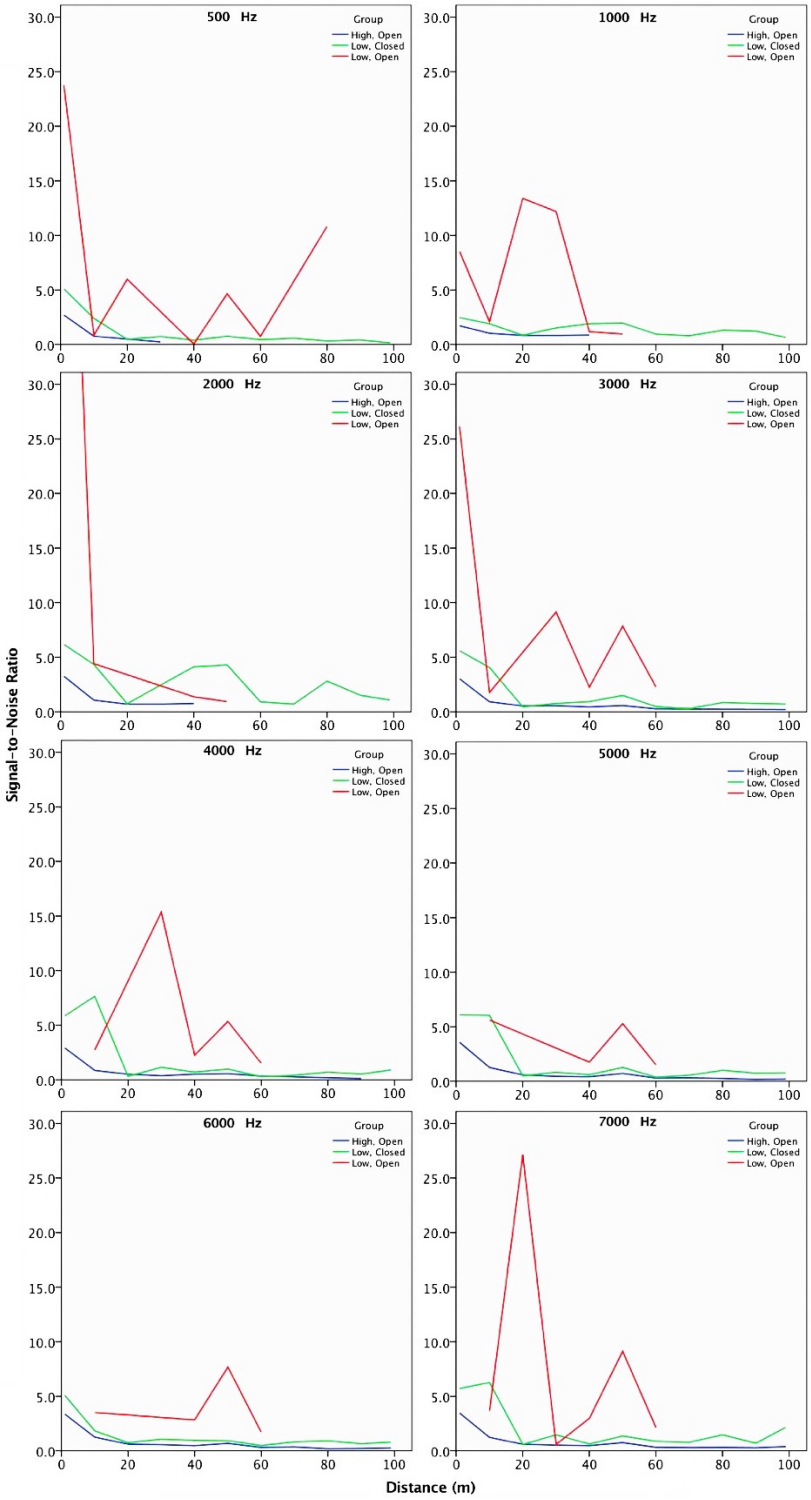

Figure 2.11. Signal to Noise Ratio (SNR) over distance from the sensor for detected generated tones from 500 – 7000 Hz. Shown within each panel is the difference in detectability from high wind, open canopy (blue), low wind, closed canopy (green), and low wind, open canopy (red).

CHAPTER 3. DETERMINING SPATIAL AND TEMPORAL PATTERNS OF PROCELLARIIFORM SEABIRD HABITAT USE ON TA‘Ū, AMERICAN SAMOA

Abstract

Tropical Procellariiform seabirds often breed on remote islands that face ecological threats, including invasive predators and habitat loss. The aim of this study was to determine what Procellariiform species were present on the remote island of Ta‘ū, American Samoa, their spatiotemporal activity patterns and habitat use overlap using Autonomous Recording Units. Between January – May, 2013 and December – April 2015, Tahiti petrel (*Pseudobulweria rostrata*) was the most widespread species and exhibited higher acoustic activity than any other species. Tropical shearwater (*Puffinus bailloni*) showed spatially different, yet relatively lower relative acoustic activity. Few calls were recorded for Herald petrel (*Pterodroma heraldica*) at only two sites. Tahiti petrel and Tropical shearwater exhibited different nightly and seasonal temporal patterns in colony attendance. Activity for Tahiti petrels was highest in April – May while Tropical shearwaters were more active in December. Additionally, calls of an unknown petrel and potential Newell’s shearwater (*Puffinus newelli*) were detected. These results indicate that Ta‘ū is an important location for Procellariiform species and that both spatial and temporal habitat partitioning is occurring. Inter-species short term colony attendance patterns indicate differences in the feeding ecology and locations of the species.

Introduction

Burrow nesting seabirds such as the Procellariiformes often breed colonially alone or sympatrically with other burrow nesting species (Weimerskirch et al. 1986, Curé et al. 2009). In cases where multiple burrow nesting seabird species occur within the same area, some level of intra- and interspecific competition may occur for burrows (Ramos et al. 1997, Sullivan and Wilson 2001, Villard et al. 2006). However, the level of interspecific competition can be minimized if sympatric species are breeding at low densities or if habitat availability is not limited (Croxall and Prince 1980, Bourgeois and Vidal 2007). Many seabird colonies host multiple species that exhibit clear foraging niche separation at sea (Cherel et al. 2008, Young et al. 2010a, 2010b). Yet, the extent to which sympatric burrow nesting seabird species exhibit niche separation of their nesting habitat is not well understood. Competition may occur due to a limitation of suitable breeding habitat (Sullivan and Wilson 2001). Thus, there is a need to further understand the ways in which groups of burrow nesting seabirds interact, and partition nesting habitat resources on their breeding colonies.

Significant gaps in our knowledge of the breeding habitat use by seabirds still exist. In particular, Procellariiform seabirds in the South Pacific Ocean are poorly understood, and for some species only cursory information about their range and breeding distribution is known. Most tropical Procellariiformes are endemic to islands (Warham 1990), and many nest on high remote mountain slopes of islands, such as Newell's shearwater (*Puffinus newelli*) and Hawaiian petrel (*Pterodroma sandwichensis*) in Hawai'i (Day et al. 2003, Simmons and Hodges 1998) and Barau's petrel (*Pterodroma baraui*) in the Mascarene archipelago (Probst et al. 2000).

Tropical Procellariidae as a group are challenging to study because they are often found nesting in remote, difficult to access sites, and are nocturnal burrow nesters (Probst et al. 2000). Surveying burrow-nesting seabirds through burrow censuses, plot counts, or banded populations is difficult (Keitt 2005), and performing burrow searches is an intrusive, often damaging technique that causes stress to birds and physical disturbance to the habitat (Ambagis 2004). These difficulties have led to a lack of information on the natural history, ecology, habitat, and threats to tropical Procellariiform species.

Passive acoustic monitoring, in which a device records surrounding acoustic signals, is well suited for studying nocturnal Procellariiform species because vocalizations are a vital component of their communication (Storey 1984, James 1985, Bretagnolle 1996). Acoustic monitoring has recently been used to investigate the presence of several seabirds, including storm-petrels in the Aleutian Islands, and Cory's shearwater (*Calonectris borealis*) in the Azores (Buxton and Jones 2012, Oppel et al. 2014). Acoustic monitoring not only provides information on presence or absence of a species, but can also provide information about sex, and the identity of individual birds (McKown 2008). Acoustic methods, through the use of Autonomous Recording Units (ARU) show particular promise for the study of threatened, endangered, or data poor species as the ARUs increase sampling effort coverage and increase understanding of colony attendance and behavior (Robb and Mullarney 2008, Buxton and Jones 2012).

Seabirds are one of the most threatened groups of birds, and gadfly petrels (*Pterodroma* and *Pseudobulweria*) are the most threatened group of seabirds (Croxall et al. 2012). Of the terrestrial threats to seabirds, invasive species are by far the biggest problem, yet human disturbance and habitat loss are also significant threats (Wilcove et al. 1998, Croxall et al. 2012).

The management and conservation of island seabirds has focused on the removal of invasive predators such as rodents, and habitat restoration (Howald et al. 2007, Jones and Kress 2012). However, a proper assessment of the threats that a particular species faces requires an understanding of phenology and behavior including inter-species interactions, and an understanding of preferential habitat conditions. The island of Ta‘ū in American Samoa is an interesting case study, as the limited summit montane habitat provides breeding habitat for multiple Procellariiform species (O’Connor and Rauzon 2004). These seabird populations face many threats including predation from rats and a loss of breeding habitat (O’Connor and Rauzon 2004).

Understanding how this group of Procellariiform species interact and use this habitat over space and time will provide useful information for how this tropical island ecosystem can best be managed. Thus, my overarching goal was to use ARUs to determine the spatiotemporal patterns of Procellariiform seabirds in a remote island context. To address this goal, I sought to answer the following questions. First, what species are present within the summit montane habitat of Ta‘ū? Second, what spatial and temporal activity patterns are present among survey sites, and to what extent do the species overlap in their use of the habitat? Finally, what other environmental or habitat conditions affect the habitat used by breeding Procellariiformes?

Methods

Study Site

To address my research questions, I selected the island of Ta‘ū in American Samoa in the South Pacific Ocean. American Samoa is an unincorporated territory of the United States

located in the South Pacific between Fiji and French Polynesia (Figure 1). Although little is known about the seabirds of American Samoa, the territory provides potentially valuable breeding habitat for several near threatened and data poor seabird species (O'Connor and Rauzon 2004). Ta'ū in the Manu'a group east of Tutuila is home to many species of Procellariiform seabirds, including Tahiti petrel (*Pseudobulweria rostrata*), Herald petrel (*Pterodroma heraldica*), and Tropical shearwater (*Puffinus bailloni*; Amerson et al. 1982, Pyle et al. 1990). The Tahiti petrel is listed as near threatened, the Herald petrel and Tropical shearwater are listed as species of least concern by the IUCN (Birdlife International 2012, 2014a, 2014b).

Ta'ū is a high volcanic shield island with a single peak that is partially collapsed (Stice and McCoy 1968). The partial collapse has resulted in a north facing gentle slope with a peak at approximately 980 m and a sharp near vertical slope to the south descending nearly 600 m to the ocean (Figure 2). Previous work has identified the montane area of the island as the breeding locations for Procellariiform seabirds (Amerson et al. 1982, Pyle et al. 1990, O'Connor and Rauzon 2004). I selected locations within the montane habitat above 650 m, located in the Ta'ū unit of the National Park of American Samoa. The summit montane region of Ta'ū is characterized by vegetation in a constant state of disturbance, dominated by understory species such as ferns and *Freycinetia* vines (Whistler 1992). Due to high levels of rainfall and periodic but frequent disturbance from high winds and hurricane damage, very few tree or canopy species are found. What canopy is present is dominated by *Cyathea* tree ferns and small numbers of tree species characteristic of the lower montane forest including *Astronidium pickeringii*, *Syzygium samoense*, and *Weinmannia affinis* (Whistler 1992).

Autonomous Recording Units

Surveys were conducted with Song Meter SM2+ (Wildlife Acoustics, Inc.) acoustic sensors due to their ability to endure harsh weather environments, affordability, and widespread use in other seabird acoustic surveys (Buxton et al. 2013, Oppel et al. 2014, Cragg et al. 2015). Each sensor was equipped with a 32 GB SD memory card to store all field recordings. Sensors were deployed in the field by attaching them to small trees at a height of approximately 1 m (Figure 3). Each sensor was powered by 16 D-cell alkaline batteries via an external battery box stored close to the sensor on the ground. The standard factory internal gain settings (48 dB) were used and recordings were made at 22,050 kHz to cover the potential range of all seabird calls expected. Each Song Meter was deployed with one SMX-II omni-directional microphone installed on the left channel, oriented horizontally to the ground and away from the prevailing wind direction. Sound files were stored as uncompressed .wav files.

Survey Design

Sensors were deployed at eight survey sites on the summit montane region of Ta‘ū within the National Park of American Samoa (NPSA) at elevations between 790 m and 966 m (Figure 4). The sensors were deployed in two distinct regions, one on the east side of the summit, and one on the west side of the summit (Figure 4). This region has been identified as having suitable habitat for the petrels and shearwaters breeding on Ta‘ū (O’Connor and Rauzon 2004, Amerson et al. 1982). The lowest elevation sensors were placed in habitat deemed to be marginal due to the presence of more secondary forest tree species, higher canopies, and fewer summit scrub and montane forest species (Whistler 1992). These lower elevation sensors

were placed with the expectation that there would be low levels of acoustic activity in the vicinity. Sensors were spaced at least 200 m apart along the only two trails leading to the summit, and in the area between these two trails, resulting in sensor spacing that maximized the spatial coverage of the survey along an elevational gradient and a habitat gradient. The minimum 200 m spacing also prevented sampling overlap between sensors (see Chapter 2) and limited habitat damage by remaining on, or close to designated trail areas. Two sensors (3, 5) were placed near the steep drop off over the south facing cliff close to the summit. These two sensors were placed to survey both the sloping summit region and the top of the cliff habitat.

Recording Schedule

Song Meter clocks were set to GMT-11 and programmed to record every other night for one minute out of every five minutes starting at one hour before sunset and recording until one hour after sunrise the following morning. Sunset and sunrise were calculated from a central GPS location (-14.23° S, -169.46° W) for all sensors. Song Meters were programmed to record in mono (left channel). The Wildlife Acoustic Inc. program SMCONFIG.exe (Version 3.2.4) was used to estimate battery life and memory card space. A single 32 GB memory card was estimated to be filled with recordings after approximately 150 days and that batteries would last approximately 10 months. Sensors were deployed in February 2014, and data were retrieved in December 2014. The Song Meter sensors were redeployed at that time with new SD cards and batteries. The data from the second deployment was retrieved in August 2016.

Equipment Failures

Song Meter SM2+ units have been reported to have experienced multiple kinds of equipment failures, especially in wet, humid, and windy climates. In some cases, water entering the song meter case through faulty gaskets has flooded the electronics. More commonly, however, water pooled on the microphone element has de-polarized the water-resistant membranes protecting the electret microphones on SMX-II microphones. The latter is difficult to detect within thousands of hours of field recordings. I used a quantitative method for detecting microphone failures that allows survey effort to be corrected when recording quality is severely depressed. Specifically, I calculated a spectral measure of "non-flat" signal activity (flux sensitive), a measure of sound energy and how it is distributed across the recording. Recordings with low signal activity identify microphones that are not recording properly. Microphones exhibited periods of low signal activity followed by recovery back to acceptable signal activity. For this project, I used a flux sensitive threshold of > 0.01 to remove suspect recordings. Detected calls were totaled and summarized as a function of actual effort by sensor and over time. During this study, I did experience both flooding and corrosion within the Song Meter case and within the external battery box case due to the constantly wet conditions. However, the de-polarization and complete failure of SMX-II microphones was even more common, resulting in a total loss of survey effort at some monitoring locations.

Finally, Song Meter firmware bugs arise occasionally as hardware components change, or as configuration software is updated. Patches to fix these software bugs are regularly sent out by Wildlife Acoustics, but sensors need to be physically reprogrammed to fix the firmware. The Song Meter SM2+ sensors used for this project contained a firmware bug that caused

errors when reading the available space on the installed SD memory cards. This bug caused the sensors to believe that the SD cards were full before they were, resulting in a loss of longer term temporal effort and for the sensors to believe the memory cards were full before the batteries had been fully discharged. The patch for this bug was only sent out after the sensors were deployed in the field and the issue was not realized until the data from the first deployment was analyzed and the sensors were already redeployed for the second round of data collection. This error led to the collection of less data because the sensors only used half of the available memory installed in each sensor.

Data Processing

Unprocessed acoustic data from each sensor were split into two-second samples (windows) for analysis. Poor quality data indicative of a microphone failure during high wind and rain conditions were removed from analysis and remaining data were processed to detect vocalizations from the species of interest using a machine learning Deep Neural Network (DNN) classification model (Conservation Metrics Inc.). The DNN method uses a classification model trained to detect a unique combination of spectro-temporal features found in target sounds. These individual elements of calls from species of interest include harmonics and tones between 500 and 7000 Hz. Trained models then were used to search field recordings for sounds with the same combination of features. Deep Neural Networks are the current state of the art for detection and classification problems in many fields including speech recognition (Deng et al. 2013) and remotely sensed image recognition (Ciresan et al. 2012). Detection models were developed for all species of interest (Tahiti petrel, Herald petrel, Tropical shearwater and one for an unknown petrel call) as all species calls are significantly different from one another. The

detection model scored all the windows based on the likelihood that they contain a call of interest on a scale of 0 – 5. All events flagged by the model detector and all sounds that returned high scores for a separate tonal filter (tones between 1 and 4 kHz often present in Procellariiform calls) that returned high scores (4 – 5) were manually reviewed and corrected as necessary.

Classified vocalizations were summarized by the number of calls per minute within 10 minute bins for each night surveyed. Average nightly activity was examined across all survey sites to determine the peak calling hour, and this specific hour was used to summarize and compare the data by day for each site. Because burrow nesting seabirds tend to be less active on colonies during moonlit nights (Watanuki 1986) I compared average nightly acoustic activity for Tahiti petrel and Tropical shearwater to moon phase (U.S. Naval Observatory). The effect of increasing moon illumination (0 – 1) as a measure of the amount of moon visible on vocal activity was examined by fitting a linear regression for each species with average nightly calls minute^{-1} as the dependent variable and moon illumination as the explanatory variable. I examined the strength and slope of the relationship to determine the extent to which moon illumination was influencing seabird acoustic activity.

Recorders were first deployed in January 2014 and recorded until May 2014 (deployment 1). Recorders were redeployed in December of 2014 and recorded until April 2015 (deployment 2). This redeployment allowed a replicate of the acoustic survey effort during the Austral summer and autumn time frame. Data from this second deployment were retrieved in August 2016 from 7 of the 8 sensors. Time and access issues in the field prevented the last sensor (sensor 8) from being retrieved.

Data Analysis

Seabird calls in the acoustic data identified using the DNN classification models were analyzed using custom Matlab (Mathworks Inc.) programs. Individual call spectro-temporal characteristics were analyzed using Adobe Audition (Adobe Inc.). Data were analyzed to identify spatial and temporal patterns of call frequency using non-parametric Mann-Whitney U tests (α = 0.05) to identify differences between species, between locations, and over time on different temporal scales. Particularly, the differences between sides of the summit were determined by comparing the average acoustic activity (calls minute^{-1}) between the east and west side sensors using Mann-Whitney U tests. The differences between deployments were determined by comparing average acoustic activity (calls minute^{-1}) between the period in which there was temporal overlap between years (overlap period = day of year 32 - 72) using Mann-Whitney U tests. The effect of moon phase on average call activity was analyzed using linear regression. Statistical tests were carried out using SPSS version 24 (IBM Corp.). Results are reported as means ± S.D., unless otherwise noted.

Results

Effort

Between January – May 2014 (Deployment 1), 1,013.41 hours of recordings were collected and analyzed from 731 combined survey nights across the 8 sites. Sensors lasted between 55 - 96 nights. Of the 32 GB available on each card, the song meters only wrote 18.9 GB of data due to software error (see above). Microphones malfunctioned from water damage

at seven sites and serious data loss (> 50%) occurred at five sites (Figure 5). After removal of low quality data, the final analyses included 531 survey nights and 468.8 survey hours. Between December 2014 – April 2015 (Deployment 2), I collected and analyzed 1,011.9 hours of recordings from 760 combined survey nights from 7 sites. Sensors lasted 95 - 141 nights. After removal of low quality data, the final analysis included 449 survey nights and 270.7 total survey hours (Figure 5).

Tahiti Petrel Activity

In deployment 1, a total of 15,352 Tahiti petrel calls were detected at all survey sites and in deployment 2, a total of 4,122 Tahiti petrel calls were detected at four of the seven sites. On a daily scale, call rate peaked 60 to 120 minutes after sunset, and this peak period was used to compare call rates between sites (Figure 6). A small number of calls were detected up to 20 minutes before sunset during the 50 minutes before sunrise, but overall most calls were detected between 40 minutes after sunset and 90 minutes before sunrise and were relatively consistent throughout the night (Figure 6). The highest mean call rate during deployment 1 was at sensor 2 (2.57 ± 2.91 calls minute^{-1}), followed by sensor 5 (1.26 ± 1.61 calls minute^{-1}) (Figure 7). The lowest elevation sensor (sensor 4) had the lowest levels of acoustic activity. In deployment 2, the highest mean call rate was at sensor 2 (0.99 ± 1.10 calls minute^{-1}), followed by sensor 5 (0.66 ± 1.51 calls minute^{-1}) (Figure 7). The lowest elevation sensor (sensor 4) had the lowest levels of acoustic activity, followed by sensors 1 and 6. Spatially, there was no difference between acoustic activity between the east and west sides of the summit region (Mann-Whitney U = 7.0, P = 0.881). However, sensors 2 and 7 were the only ones that did not

experience catastrophic data loss due to microphone failure. Thus, although total call rates are corrected for effort, sensors 2 and 7 show the most complete representation of long term acoustic activity. Seasonally, there were lower levels of acoustic activity between December and March, with higher levels of activity in April and May (Figure 8). In the overlap period between Day of Year 32 – 72 where sampling effort was present in both 2014 and 2015, acoustic activity was higher in 2014 (deployment 1) than in 2015 (deployment 2) (Mann-Whitney U = 621, $P = 0.02$).

Tropical Shearwater Activity

A total of 413 Tropical shearwater calls were detected at all survey sites except sensor 3, the lowest elevation site during the first deployment. During the second deployment, a total of 631 Tropical shearwater calls were detected at sensors 2, 3, 5, and 7 (Figure 7). On a daily scale, call rate peaked 40 to 100 minutes after sunset for both deployments (Figure 6), and this peak period was used to compare call rates between sites. There was a second peak in activity between 80 and 10 minutes before sunrise. There were only a few calls detected between 120 minutes after sunset and 40 minutes before sunrise. The highest mean call rate during deployment 1 was at sensor 2 (0.21 ± 0.27 calls minute^{-1}), followed by sensor 3 (0.19 ± 0.33 calls minute^{-1}). The highest mean call rate during deployment 2 was at sensor 2 (0.29 ± 0.76 calls minute^{-1}), followed by sensor 5 (0.1 ± 0.22 calls minute^{-1}) (Figure 7). Spatially, Tropical shearwater activity was higher on the west side of the summit, and the lowest elevation west side sensor had higher call rates than any of the east side sensors (Mann-Whitney U = 0.0, $P = 0.025$). Again, sensors 2 and 7 had the lowest data loss from microphone failure, representing

the most complete records of acoustic activity. Seasonally, there were increased levels of acoustic activity in December, and overall low levels of activity between January and May (Figure 8). Interannual comparisons in the overlap period between 2014 and 2015 (Day of Year 32 – 72) showed acoustic activity was not different between years (Mann-Whitney U = 1.0, P = 0.053).

Herald Petrel Activity

Herald Petrel calls were detected at two survey sites on the west side of the summit (sensor 1, 2) during deployment 1. On a daily scale, call rates peaked during the hour before sunset and this peak period was used to compare call rates between sites. Of the total calls detected, only two calling bouts were detected after sunset and no calls were detected after 160 minutes after sunset. The highest mean call rate was at sensor 2 (0.09 ± 0.26 calls minute^{-1}), followed by sensor 1 (0.05 ± 0.23 calls minute^{-1}). All Herald petrel calls were found at the higher elevation sites on the west side of the summit region. No Herald petrel calls were detected during deployment 2. Once again, sensor 2 had the highest survey effort, and the highest call rates. Seasonally, recordings from sensor 2 indicate that there was more vocal activity later in the monitoring period (specifically from mid-March onward). However, Herald petrels are diurnal and sensors were not primarily set to monitor during daylight hours.

Unknown Petrel Activity

During my analysis, I detected an unidentified petrel call type that was consistently detected during the survey period (hereafter 'unknown petrel'). These calls were detected at three survey sites during deployment 1, two on the west side of the summit (sensor 1, 2) and

one on the east side (sensor 8). During deployment 2 the unknown petrel was detected at two sites, one on either side of the summit (Sensor 2, 7). On a daily scale, the unknown petrel call peaked during the hour before sunset, however, calling continued at consistently low levels throughout the night. Call rates were therefore calculated using recordings from the entire night. No calls were detected from 40 minutes before sunrise onward. The highest mean call rates were recorded at sensor 2 (0.046 ± 0.178 calls minute^{-1}), followed by sensor 1 (0.006 ± 0.041 calls minute^{-1}). Call rates were very low during deployment 2 (< 0.001 calls minute^{-1}). As with other species, call rates at sensor 2 may be related to the fact that sensor 2 represented a more complete record of acoustic activity. Seasonally, detections showed a clear peak in activity during the end of March, where there was a several day stretch where high call rates were present at the two sites during deployment 1 (Sensors 2, 8).

Newell's Shearwater Type Call

I detected a single unidentified seabird call at sensor 7 on 10 February 2014 at 03:16 during deployment 1. The call was not a Tropical shearwater call, and most resembled calls of Newell's shearwater (*Puffinus newelli*), a species that breeds in Hawai'i (Ainley et al. 1997). The detected call was most similar to a call from a bird in flight, because of the variation in call intensity. The call consisted of two phrases made up of a longer initial exhale note followed by inhale/exhale pairs in rapid succession and ending with a longer exhale note (Figure 9). The calls had two to four clear harmonics. The fundamental frequency of the exhale note was 895 Hz and average 0.1 second in length (n = 4) and the fundamental frequency of the inhale note 776 Hz and averaged 0.08 seconds (n = 3). The initial syllable had a fundamental frequency of 1,875 Hz

and a mean length of 0.31 seconds (n = 2). The final syllable had a fundamental frequency of 660 Hz and a mean length of 0.295 seconds (n = 2; Figure 9). I used a previously developed Newell's shearwater classification model from Kaua'i to search for additional calls on two file-streams (Sensor 7, 8) and manually reviewed all recordings from the three nights on either side of the call detected; no other Newell's shearwater-like calls were detected.

Moonlight Effect

I examined levels of acoustic activity as a function of moon presence for both Tahiti petrels and Tropical shearwaters. Data on daily calls minute^{-1} from both deployments were pooled and the effect of increasing moon illumination as a measure of the amount of moon visible on vocal activity was examined by fitting a linear regression for each species. There was no significant pattern between moon illumination and call rate for either species (Figure 10). Tahiti petrel acoustic activity could not be well predicted from moon illumination (r^2 = 0.08, calls minute^{-1} = 0.30 + 0.59 * illumination). Tropical shearwater acoustic activity also could not be well predicted from moon illumination (r^2 = 0.035, calls minute^{-1} = 0.61 + 1.772 * illumination). However, this analysis does not account for cloud cover which could obscure moonlight.

Discussion

The results show that over the two years, five species of Procellariiform seabird species were detected on the summit of Ta'ū, possibly including the Newell's shearwater, and an unidentified petrel. The Tahiti petrel was found to have the highest vocal activity and most

widespread distribution. Spatially, the west side of the summit had higher levels of Tropical shearwater activity and the highest diversity with all detected species present. Both the Tahiti petrel and Tropical shearwater were nocturnally active at the colony and temporally were present at the colony throughout the study period. Furthermore, over the study period both the Tahiti petrel and Tropical shearwater showed spikes in acoustic activity that may be indicative of different phenological patterns and an increase in breeding activity during different periods of the year.

This pattern of Tahiti petrels and Tropical shearwaters arriving at the summit colony shortly after sunset is to be expected as both species are nocturnally active at their colonies (Bretagnolle et al. 2000, Rauzon and Rudd 2014). A similar pattern is seen in Hawaiian petrel, which begin their movement onshore towards mountain top colonies during the crepuscular period (Day and Cooper 1995). Two of the major components of acoustic communication within the Procellariidae are flight contact calls and major calls which are involved in courtship (Bretagnolle 1996). Because the flight call is often a truncated version of the major courtship or contact call (Bretagnolle 1996, Rauzon and Rudd 2014), separating these calls from each other in recorded audio data is difficult both manually and via automated methods.

The six-month presence of both Tahiti petrel and Tropical shearwater at the colony indicates that both species may lack a defined breeding season at this colony. However, the lack of data during June – November means that it is still unclear if there is a period of the year with no seabird activity. Increased vocal activity periods in April – May for Tahiti petrel and December for Tropical shearwater indicate that there is probably a season of increased nesting activity for both species. Previous reports have suggested that July may be a peak fledging time

for Tahiti petrels in American Samoa (Amerson et al. 1982), supported by reports of chick fall out during the Austral winter on Tutuila (MacDonald, unpublished data). Breeding periods for Tahiti petrels in French Polynesia are thought to be between March and October (Holyoak and Thibault 1984, Brooke 2004). However, egg laying has been documented in Tahiti throughout the year (Villard et al. 2006). In New Caledonia, Tahiti petrels breed throughout the year with the peak in fledging occurring between July and September, with the time from egg laying to fledging reported as approximately 150 days (Villard et al. 2006). An increase in vocal activity of Tahiti petrel in April and May would coincide with an increase in laying activity, which would fit with a timeline for increased fledging in the Austral winter. The potential partitioning of the summit habitat, indicated by the different spikes in activity of Tahiti petrel and Tropical shearwater, may point to suitable habitat as a limiting factor for breeding populations that the habitat can support. For example, in New Caledonia, availability of habitat is limited and Tahiti petrels are outcompeted for burrows by Wedge-tailed shearwaters (*Puffinus pacificus*), potentially reducing their ability to breed (Villard et al. 2006).

Spatially, species composition and acoustic activity rates differed between survey points on the eastern and western sides of the summit. The western side of the summit (sensors 1 -3) showed higher call rates for Tropical shearwater and Herald petrel calls were only found on the western side of the summit. In general, habitat structure differed between the eastern and western sides of the summit. The eastern side is dominated by *Freycinetia storkii* vines, interspersed with small tree ferns and trees, while the west side of the summit is characterized by higher densities of trees and tree ferns, and a more open understory (Whistler 1992). These differences could be caused by the high disturbance, continually wet and windy conditions

across the summit region (Whistler 1992). These data suggest that the less disturbed habitat found on the western side of the summit may be preferred by Tahiti petrel, Tropical shearwater, and ground nesting Herald petrel, although other unknown factors may also be contributing to the observed differences. It must be noted that condition dependent differences in the detection range of each sensor may also be contributing to the spatiotemporal differences in acoustic activity (Chapter 2). Additional measurements of habitat characteristics around survey sites are recommended. A better understanding of how Ta‘ū summit habitat structure is influenced by the prevailing weather conditions would lead to a better understanding of how habitat structure variation is driving Procellariidae nesting locations on Ta‘ū.

The sensors on the western side of the summit were also the only sites where the unknown petrel calls were detected. The pre-sunset peak in activity of these calls was similar to Herald petrel activity at these sites, suggesting that the unknown petrel call might be a previously unknown alternate Herald petrel call. Additionally, several aggressive interactions between individuals can be heard on the recordings. More data from experts working with Herald petrels in other locations, and more data from Ta‘ū, including acoustic and visual surveys are needed to confirm this conclusion. The presence of a potential Newell’s shearwater on Ta‘ū would represent the second occurrence of this species in American Samoa (Grant et al. 1994). Newell’s shearwater disperse from Hawai‘i during the non-breeding period, but are rarely found south of the equator (Onley and Scofield 2007). The presence of only a single call is not enough to conclusively say that a Newell’s shearwater was present on Ta‘ū, particularly given

that both Newell's shearwater and Tropical shearwater are taxonomically within the same Little/Audubon's shearwater complex (Onley and Scofield 2007).

Many Procellariidae species are nocturnally active on their colonies, which may reduce the threat of predation from certain native predators. Because Procellariidae calls tend to be loud, repetitive, and highly distinctive, this behavior can put them at risk from predation. Many Procellariidae species also avoid the colony on moonlit nights which also reduces predation risk (Imber 1975, Mougeot and Bretagnolle 2000, Miles et al. 2010). This study found no correlation between moon illumination and acoustic activity at the colony. This lack of correlation could indicate both species have no need to avoid the island due to the absence of predation pressure. Specifically, there are no predatory skuas, or gulls, and only bird of prey, the Barn owl (*Tyto alba*) present on Ta'ū (Steadman 2006) which could cause the birds to avoid moonlit nights. In contrast, Brown rats (*Rattus norvegicus*) are present on the summit of Ta'ū and would be a potential threat to the birds given their nocturnal feeding behavior (O'Connor and Rauzon 2004, Jones et al. 2008). However, while I investigated the effect of moon illumination, there are no data on cloud cover, actual light levels at the colony, or rainfall. Because the summit of Ta'ū is more often cloud covered, moonlight at this location may be so infrequent, thus not triggering a behavioral response.

The outcomes of this study faced a number of limitations mainly due to issues and malfunctions associated with the ARUs. The harsh conditions faced on Ta'ū, including the constantly wet and windy environment put a great strain on the ability of the equipment to withstand moisture intrusions. Further work to improve the performance and weather-proof microphones would increase the usefulness of these ARUs. A further limitation concerns the

ability for the measurements of call frequency from these ARUs to be translated into numbers or densities of animals detected. In addition to collecting more information about the vocal behavior and calling rates of the target species, understanding more about the environmental conditions, particularly wind speed and rainfall, at and around the ARU is important. The deployment of weather sensors in concert with the ARU would allow for a greater understanding of how these environmental conditions affect ARU performance over fine time scales.

The results of this study highlights the ability of acoustic surveys to reveal long-term detailed information about the behavioral patterns of cryptic seabirds nesting in remote locations. Not only can acoustic surveys through the use of ARUs reveal information about the distribution and habitat use of nesting seabirds over time, but can also be useful in detecting rare or unusual species. Particularly throughout the Pacific there are many remote islands which are not often surveyed, indicating that we likely don't understand the full extent of the distribution and habitat resource use of many burrow nesting Procellariidae species. Further, understanding the phenology and timing of nesting habitat use throughout the year is important for conservation planning purposes. It is important to time conservation actions such as invasive species eradications so as to avoid non-target species mortality (Hoare and Hare 2006, Howald et al. 2007). Protecting summit scrub and montane habitat should be a priority concern not only in American Samoa, but across the entire South Pacific region as it may provide important habitat for many burrow nesting Procellariidae species.

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Figures

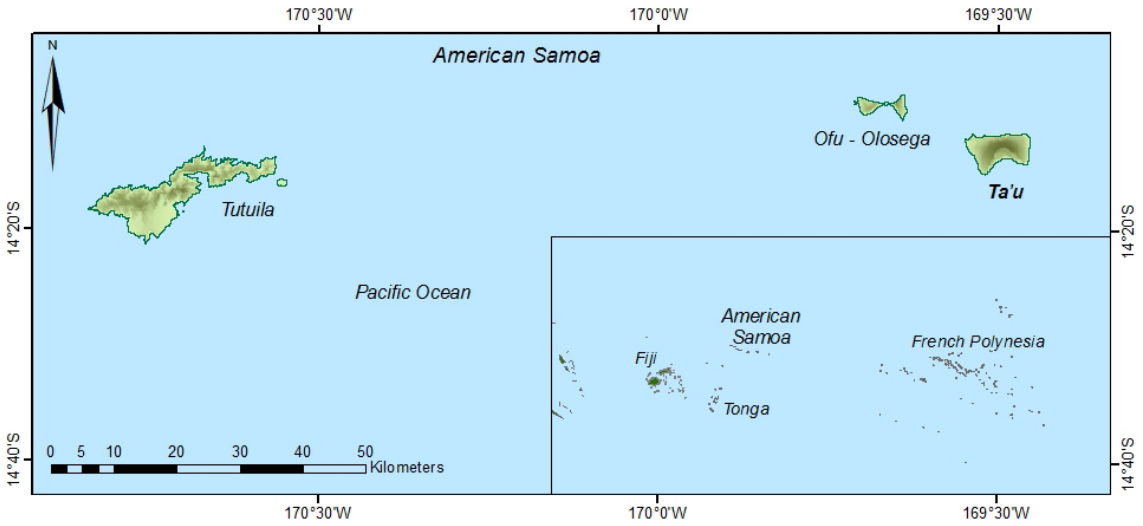

Figure 3.1. Map of the territory of American Samoa including the island of Taʻū in the Manua group of islands, located approximately 130 kilometers east of Tutuila.

Figure 3.2. At the summit of Mt. Lata on the island of Ta‘ū looking out over the south facing cliff down to the Lafuti shelf and the ocean.

Figure 3.3. Song Meter SM2+ acoustic sensor deployed in a tree within the summit montane habitat on the island of Ta‘ū.

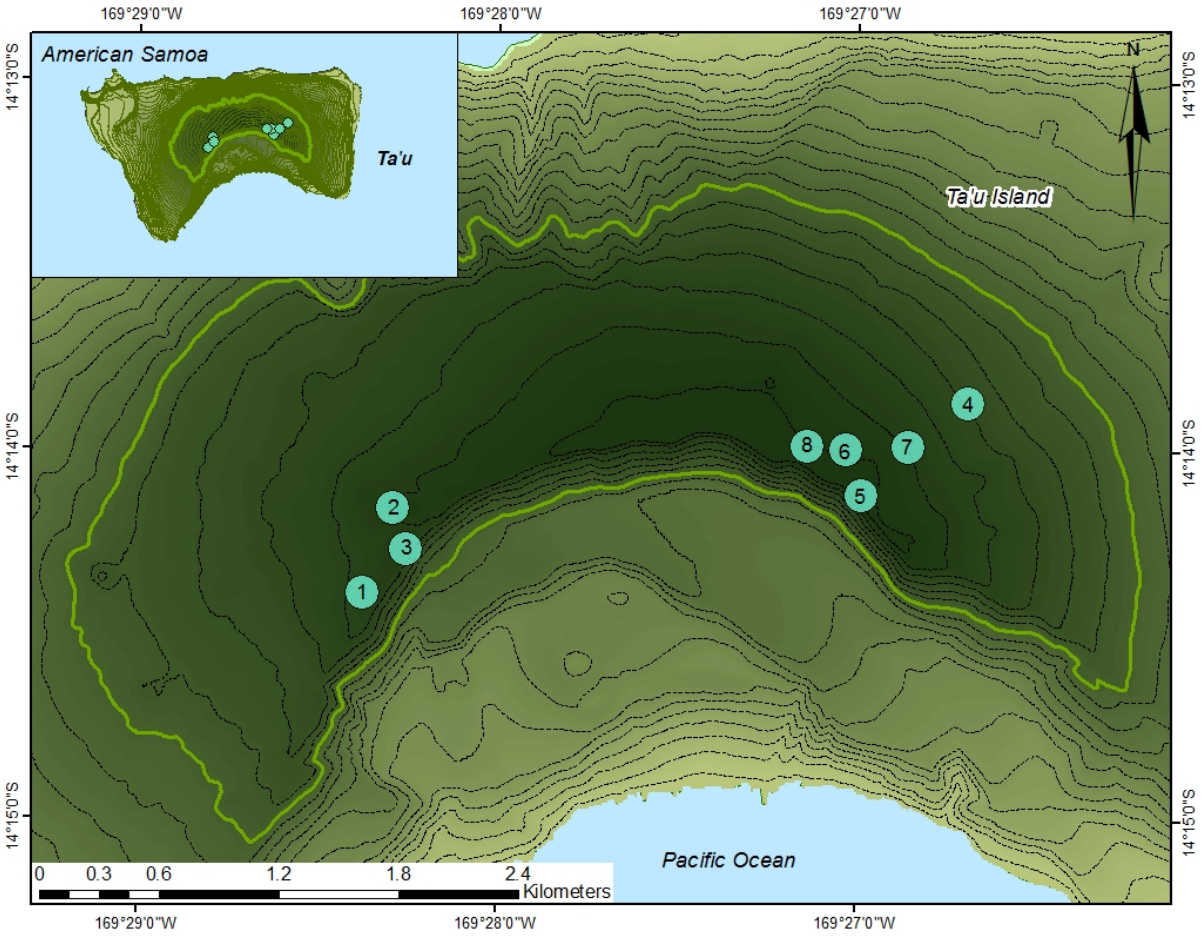

Figure 3.4. Map of the summit of Mt. Lata on the island of Taʻū and the location of the eight Song Meter SM2+ acoustic sensors.

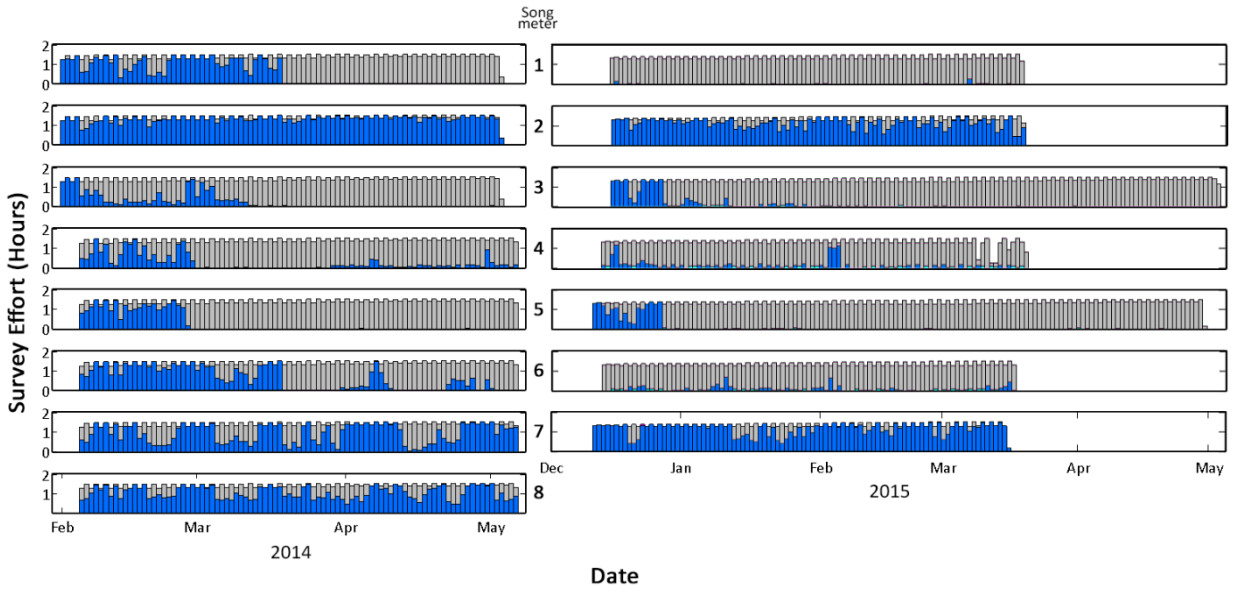

Figure 3.5. Hours of recording effort at each survey site during deployment 1 (left) and deployment 2 (right). Grey portions of bars represent poor quality recordings removed based on a measurement of microphone performance.

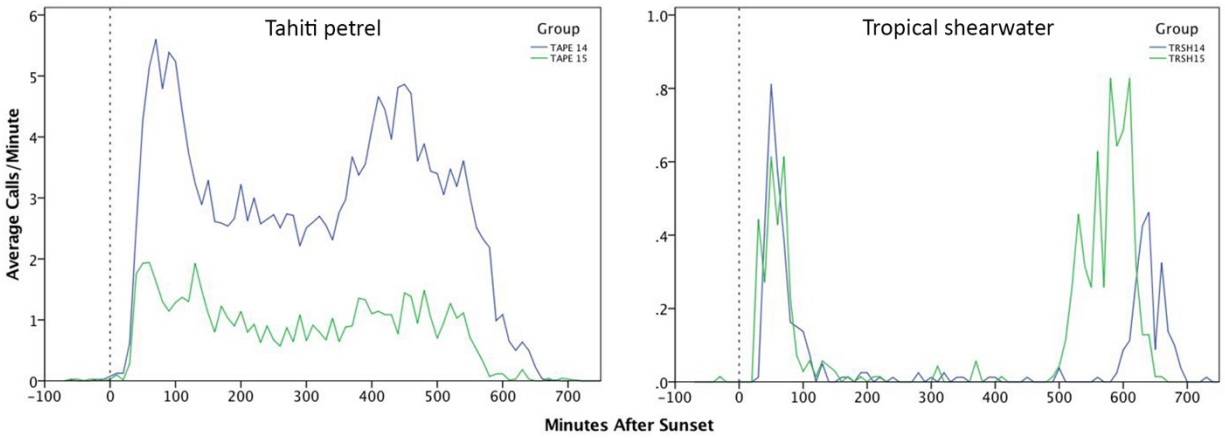

Figure 3.6. Mean vocal activity as a function of time from sunset for Tahiti petrel and Tropical shearwater. Both deployment 1 (blue) and deployment 2 (green) are shown in the panels. Data is aggregated from all sites, and all nights.

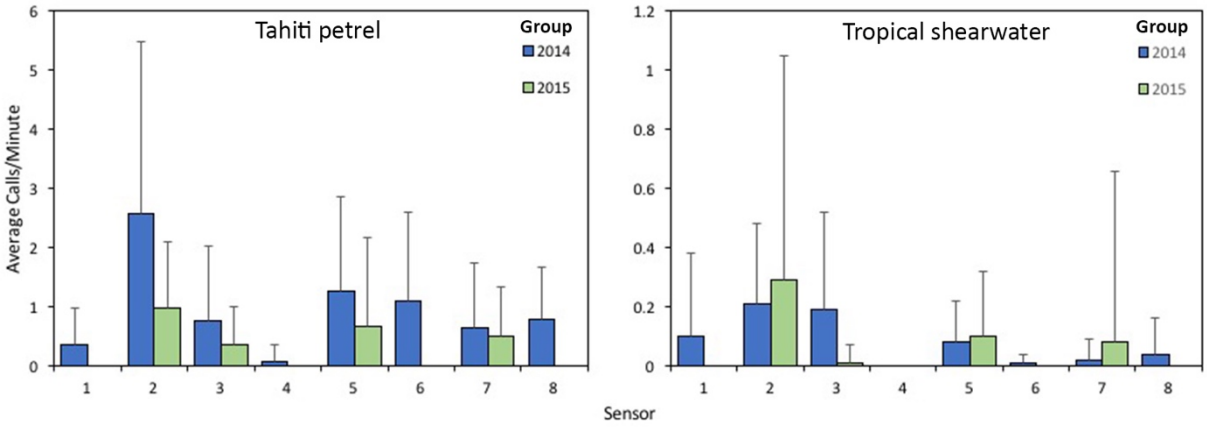

Figure 3.7. Mean vocal activity for Tahiti petrel and Tropical shearwater at each sensor for deployment 1 (January – May 2014; blue), and deployment 2 (December 2014 – April 2015; green). Note the different y-axis scales.

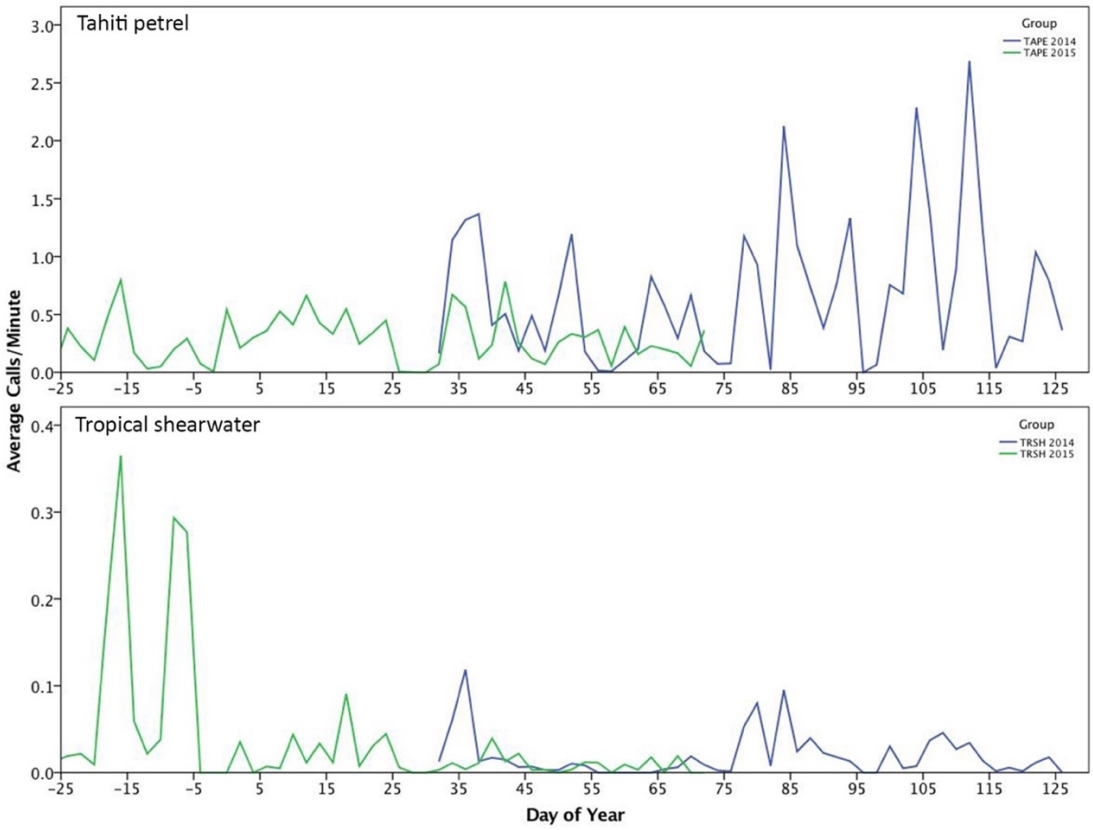

Figure 3.8. Mean vocal activity for Tahiti petrel and Tropical shearwater by day of year for deployment 1 (January – May 2014; blue), and deployment 2 (December 2014 – April 2015; green). Note the different y-axis scales.

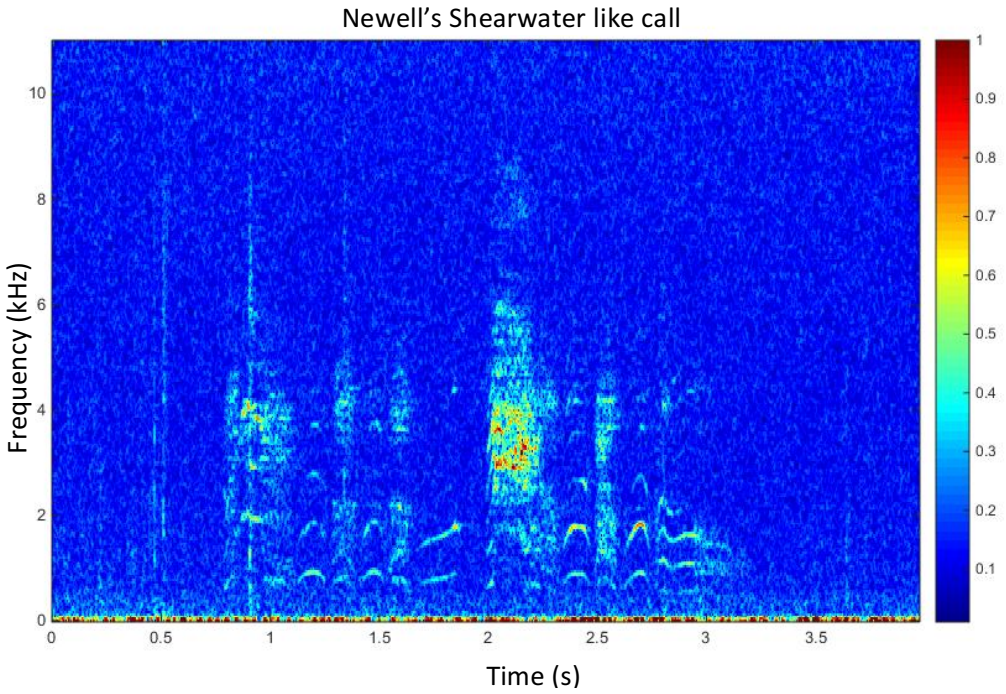

Figure 3.9. Newell's shearwater like call. Only one call was detected.

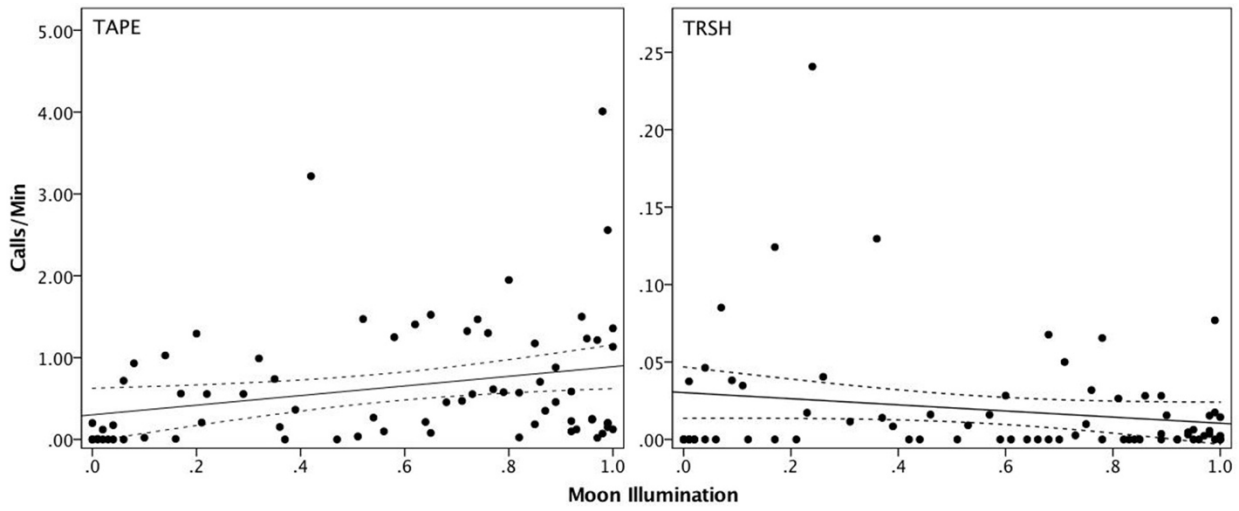

Figure 3.10. Mean acoustic activity by moon illumination value for Tahiti petrel (left) and Tropical shearwater (right) when the moon was visible between sunset and sunrise. Shown is the best fit linear regression line and 95% confidence intervals (dashed lines).

CHAPTER 4. MODELING HABITAT PREFERENCES OF TAHITI PETREL (*PSEUDOBULWERIA ROSTRATA*) ON TA‘Ū, AMERICAN SAMOA

Abstract

This study used a Species Distribution Modeling approach to determine what habitat, physical, and environmental characteristics affect Tahiti petrel (*Pseudobulweria rostrata*) nesting presence and the distribution of suitable habitat across the summit region on Ta‘ū, American Samoa. Closed canopy cover and higher altitudes best predicted Tahiti petrel nesting locations. I classified the summit montane rainforest habitat above 650 m by the presence of canopy species using supervised image classification. Of 774.7 ha of habitat classified, 63.8% was covered by canopy species. A total of 254.1 ha of montane habitat was classified as most suitable for petrel nesting. Closed canopy cover was higher on the leeward side of the summit habitat (80.02%) compared to the windward side of the habitat (46.50%). These habitat differences are likely to be caused by a combination of the prevailing wind conditions and disturbance from storm events. Strong storms and hurricanes cause significant change and damage to the amount and distribution of canopy vegetation which provide habitat for Tahiti petrels. The importance of vegetation as nesting habitat highlights the necessity to consider available habitat when determining the conservation needs of Procellariiform seabird species.

Introduction

Seabirds are important upper trophic level predators that provide a key link between terrestrial and marine ecosystems as they move nutrients, from oceans to land via guano (Polis and Hurd 1996). This movement can stimulate primary productivity, structure plant communities, and shape terrestrial food webs (Croll et al. 2005, Hutchinson 1950, Anderson and Polis 1999). In arid areas, seabirds transfer nutrients onto otherwise arid and unproductive islands ecosystems and support high densities of arthropods (Polis and Hurd 1996, Sánchez-Piñero and Polis 2000). Even in temperate, productive terrestrial ecosystems, the nutrients provided by seabirds lead to increased abundance of animals in multiple trophic levels including invertebrates and lizards (Markwell and Daugherty 2001). Hence, when seabirds are extirpated from islands or their numbers are reduced, it may have a significant impact on nutrient availability to the terrestrial ecosystem (Wardle et al. 2009). For example, extirpation of seabirds from islands can lead to lower soil fertility due to the loss of nutrient inputs leading to cascading effects on belowground ecosystems (Fukami et al. 2006).

Seabird populations are increasingly threatened by a host of direct and indirect human threats, including impacts from habitat loss, driven by factors such as invasive species, and climate change (Grémillet and Boulinier 2009, Croxall et al. 2012, Doney et al. 2012). In the case of high tropical islands, montane rainforests are predicted to experience reductions in cloud immersion, rainfall changes, and increases in hurricane frequency (Loope and Giambelluca 1998, Foster 2001). Pelagic seabirds are particularly vulnerable to threats, due to small breeding populations restricted to few breeding locations and slow population growth (Croxall et al. 2012). Island breeding Procellariiform seabirds, one of the most threatened group of birds

(Baillie et al. 2004), are of particular conservation interest given their small population sizes and scarcity of breeding locations (Croxall et al. 2012). Due to the cryptic nature and remote breeding locations of many gadfly petrels and shearwaters, there is a lack of data available for many of these Procellariiform species (Warham 1990, Towns et al. 2011). As a result, determining the habitat characteristics that define suitable breeding habitat for these species, and the extent of that habitat, is important for determining the status and conservation needs of any species.

The determination and classification of how species associate with each other is a field that has developed increasingly complex statistical approaches to understand how species interactions shape their distributions. For example, predictive habitat modelling uses resource selection functions to characterize the terrestrial niche of the species by linking the presence of a species with surrounding ecological predictors (Guisan and Zimmermann 2000). Predictive habitat models, or species distribution models (SDM), reflect the influence of limiting factors, disturbances, and resources on species (Guisan and Thuiller 2005, Algar et al. 2009, Wisz et al. 2013). Species distribution models have proliferated in recent years with an expansion in the methods available to properly encompass the variation in habitats, populations, and complexity of ecosystems (Franklin, 2010). Particularly, while SDMs were initially built to model the relationships between species and their associated abiotic factors, more recent modeling approaches have increasingly incorporated biotic relationships such as interspecific competition (Guisan and Zimmermann 2000, Guisan and Thuiller 2005, Heikkenin et al. 2007, Meier et al. 2010). While modeling approaches to spatial distribution of species has become popular, the omission or lack of ecological data limits their usefulness (Austin 2002). However, SDMs are a

tool that can be used to manage threatened species, understand the effects of climate change, and understand patterns of biological invasions (Guillera-Arroita et al. 2015). Species distribution modeling techniques have been successful in determining colony size and population distribution for many burrow nesting Procellariiformes, including Cook's petrel (*Pterodroma cookii*), Sooty shearwater (*Puffinus griseus*), Mottled petrel (*Pterodroma inexpectata*), and Hawaiian petrel (*Pterodroma sandwichensis*; Rayner et al. 2007, Scott et al. 2009, VanZandt et al. 2014).

Because habitat characteristics are valuable predictors for determining nesting locations and densities of seabirds, incorporating habitat information into conservation planning is important (Rayner et al. 2007, Scott et al. 2009, Caughley 1994). The goal of this study was to build and use a SDM to determine what differences in habitat structure, physical characteristics, and environmental conditions affect Tahiti petrel nesting presence on Ta‘ū. Further, this study investigated how the important habitat characteristics for nesting can be used to identify the fine scale extent and location of suitable Tahiti petrel nesting habitat throughout the summit region of Ta‘ū. By addressing these goals this study will provide estimates on the type and quality of habitat where Tahiti petrel nests are found on Ta‘ū. This information will be useful for determining the importance of the habitat on Ta‘ū for the regional population of the Tahiti petrel.

Methods

Study Site

Field work was conducted on the island of Ta‘ū (14.2329°S, 169.4623°W), located in the Manu‘a group of islands, 128 km east of the main island of American Samoa, Tutuila (Figure 1). The territory of American Samoa is located in the South Pacific Ocean and is located west of French Polynesia, and north of Tonga (Figure 1). There are five main islands in the territory including the main island of Tutuila, and the Manu‘a group of islands made up of Ofu-Olosega and Ta‘ū. The volcanic island of Ta‘ū is the highest point in the Samoan Islands and provides breeding habitat for a suite of Procellariiform species, including the Tahiti petrel (*Pseudobulweria rostrata*) (Amerson et al. 1982). Ta‘ū is a high volcanic shield island with a single peak that is partially collapsed (Stice and McCoy 1968). This collapse resulted in a gentle, north-facing slope with a peak at approximately 980 m and a sharp, near-vertical slope to the south descending nearly 600 m to a shelf comprised of caldera deposits and the ocean (Stice and McCoy 1968). I focused my field research on the Ta‘ū unit of the National Park of American Samoa within montane habitat above 650 m previously identified as breeding habitat for Procellariiform seabird species, including Tahiti petrel (Amerson et al. 1982, Pyle et al. 1990, O’Connor and Rauzon 2004). The high montane region of Ta‘ū is split into two different zones; montane forest, and summit scrub. These zones are characterized by constant disturbance to the vegetation, dominated by understory species such as ferns and *Freycinetia* vines (Whistler 1992). As a result of high levels of rainfall (~ 2500 mm y^{-1}) and periodic but often severe disturbance from high winds and hurricane damage, fewer tree species are found. The forest

canopy is dominated by *Cyathea* tree ferns and small numbers of tree species are found in the lower montane forest including *Astronidium pickeringii*, *Syzygium samoense*, and *Weinmannia affinis* (Whistler 1992).

Sampling Design – Control Plots

To determine the relationship between habitat characteristics and the presence of Tahiti petrel burrows on Taʻū, I compared the characteristics of habitat surrounding petrel burrows (burrow habitat) with habitat surrounding randomly available habitat (random control habitat) in the summit area on Taʻū. Random habitat control plots were selected using a random number generator that determined the distance in meters along the trail from the summit. A total of 32 habitat control plots were sampled during this study. Random survey sites were restricted to the accessible habitat off of the main trail to reduce habitat damage. At each randomly selected site, the habitat was characterized 3 m off of the trail on either the left or right side of the trail. Control plots which overlapped or were within 6 m of each other were eliminated from consideration.

Petrel Burrow Plots

General search areas with likely petrel presence were determined using acoustic surveys from seven monitoring sites established for bird monitoring (Chapter 3). Areas surrounding the acoustic survey sites and along established trail areas were surveyed for the presence of recently used petrel burrows or hollows. Search parameters indicating the presence of a burrow included the removal of leaves, mold, and litter from hollows under the roots of trees,

presence of bare mud or clearly excavated soil (Figure 2). Identified burrows were marked with flagging tape and their location was recorded with GPS (Garmin GPSMap 64, 3 m accuracy). A total of 25 petrel burrow plots were identified and sampled in the course of the study. Physical characteristics of the burrow, including the width, height, and depth of the burrow or hollow entrance, as well as the immediate vegetation were described at each burrow. The tree species closest to the burrow was also recorded. Access and time for searching were limited on the leeward (west) side of the summit by the lack of permanent trails in this area of the island, thus searching effort was focused on the windward (east) side of the summit. None of the burrows identified were occupied when found. For safety reasons, all burrow searches were conducted during the day when petrels would have been at sea. Remote infrared game cameras (Reconyx HF900) placed at the entrances of identified burrows confirmed that the burrows were occupied with Tahiti petrels at night (Figure 2).

Sampling Design

Between July 28 and August 10, 2016, a suite of habitat variables were measured at both random and burrow sites across the summit scrub region of Ta‘ū. Habitat attributes included vegetation characteristics were measured at each site using a modified Braun Blanquet cover abundance scale (Braun-Blanquet 1932). Vegetation was split into two distinct layers, ground cover layer (0-2 m from the ground) and canopy cover layer (above 2 m). Survey plots at each site were 3 m radius from either the center of the randomly selected location or the burrow entrance (VanZandt et al. 2014). Within each circular plot the percent cover of each plant form type was visually estimated. Ground cover was identified to plant form, including

grass, shrub, forb, fern, and moss, and as two individual species, *Freycinetia storkii*, and *Clidemia hirta*. The percent cover of litter, logs, rock, and bare ground was also estimated to characterize the dominant ground cover type at each plot. Canopy trees and ferns (above 2 m tall) were identified to species and used to determine the prevalent canopy cover species. Canopy closure was measured using a convex crown densiometer (Forestry Suppliers Inc.) by averaging four measurements at the cardinal directions. Percent canopy closure was used to categorize the plot into a canopy cover type as either open (< 25% cover) or closed (> 25% cover) based on widespread use of this threshold value (Hansen et al. 2010, VanZandt et al. 2014).

In addition, I estimated height of the canopy and counted numbers of both trees and tree ferns in each plot to determine the dominant canopy species. Geographic position, altitude and aspect were determined from GPS. A Digital Elevation Model (Fagatele Bay National Marine Sanctuary GIS Data Archive) was used within a Geographic Information System (GIS; ArcMap, ESRI Inc.) to determine the slope at each plot site.

Species Distribution Model

I determined the most important habitat variables that influence Tahiti petrel nest site selection using a forward stepwise binomial logistic regression with the burrows as the cases, and the random plots as controls. Binomial logistic regression has been used to identify habitat features most closely correlated with the presence of animals including seabirds, bats, and wolverines (Ford et al. 2005, Copeland et al. 2007, VanZandt et al. 2014). The logistic regression models were built using the independent explanatory variables of altitude, aspect, canopy

cover type, dominant ground cover type, dominant canopy species, number of trees, and number of tree ferns. Logistic regression models were built with the logit-link function and conditional stepwise selection based on the significance of the score statistic. Models were evaluated for fit by using the Hosmer-Lemeshow goodness of fit test ($P > 0.05$ is a good model fit), and individual parameters were evaluated for significance using a $P < 0.05$ as the cutoff value. The models with the highest explanatory power, and number of significant variables were identified based on the lowest Aikakes Information Criterion (AIC) and the final model chosen using model fit values (Hosmer-Lemeshow GOF). The environmental and habitat explanatory variables were first checked for multicollinearity based on variance inflation factor (VIF ≥ 5). Where variables were significantly collinear, only one was chosen as an input into the logistic regression model. The logistic regression model was built using presence or absence of a Tahiti petrel burrow as the dependent variable. Altitude (m), aspect, number of trees, and number of tree ferns were continuous independent variables. Canopy cover type, dominant canopy species, and dominant ground cover vegetation type were categorical independent variables. Results of the logistic regression model were used to determine the extent of suitable habitat on Ta‘ū.

Determination of Suitable Habitat

Using the results of the logistic regression SDM modeling, I applied the results of the best model to map suitable Tahiti petrel habitat using the presence of canopy cover. I classified the summit montane rainforest habitat above 650 m on Ta‘ū by vegetation type, splitting tree cover from open ground cover. A high resolution 2012 USDA NRCS Orthoimage of Ta‘ū (USDA

2016) was analyzed using GIS to classify the vegetation types present over the summit habitat. This satellite image contained multispectral bands with a resolution of 0.3 m which allowed for individual trees to be identified within the image by shape and color. The image was first clipped to restrict analysis to altitudes over 650 m as this was the area delineating montane rainforest habitat (Whistler 1992). The steep, south-facing cliff section was removed from the analysis due to significant shadowing which prevented accurate classification. The image was the most recent image available which had the lowest amount of cloud cover. Overall, I classified 774.72 ha of habitat and was unable to classify 31.18 ha of the area, which was not visible in the satellite image due to cloud cover. The imagery was classified in GIS using a maximum likelihood supervised classification model to distinguish between open ground cover areas dominated by *Freycinetia* vines and ferns, and closed canopy areas where trees and tree ferns were present. Over 150 training areas were created based on identifiable features, classifying pixel color into four categories: trees, open ground cover, bare earth, and cloud cover. Results of the image classification were used to determine the surface area covered by each category. Image classification results were then compared to the assessments of canopy cover from field plots to determine whether the fit of the model was appropriate (Lauer and Aswani 2008, Kirui et al. 2013, VanZandt et al. 2014). Due to inherent GPS position errors, the percent canopy cover of each field plot was compared to the estimated canopy cover from a larger 6 m radius plot on the classified image.

The habitat classification was then combined with the digital elevation model to create a weighted habitat suitability index within GIS. Both altitude and habitat type were binned into five categories from least suitable (5) to most suitable (1). Altitude values were binned into

equal categories; 650 – 719 m (5 – least suitable), 720 – 789 m (4), 790 – 859 m (3), 860 – 929 m (2), 930 – 998 m (1 – most suitable). The four habitat type values were categorized as follows; Open (1 – most suitable), Bare (3), Closed (5 – least suitable), Cloud (excluded from analysis). The final suitability index was weighted towards habitat type (0.75) due to its greater importance in determining burrow location. This analysis provided an assessment of the amount of likely suitable nesting habitat present over the summit of Ta‘ū.

Results

Burrow Site Descriptions

A total of 25 Tahiti petrel burrows were found on the summit of Ta‘ū (Figure 3), with 16 located on the windward (east) side of the summit region surrounding the Lata summit between 793 m and 966 m, and nine burrows located on the leeward (west) side of the summit close to the Olotania crater. All burrows were found within hollows underneath small trees or tree ferns, with the root structure of the tree or fern above providing an open space for nesting (Figure 3). There were often multiple openings to the burrows within the exposed root system. However, usually there was a single large, apparent opening to each burrow. The most common tree species found giving root structure to the petrel burrows was *Weinmannia affinis* (42%), followed by *Cyathea* tree ferns (36%), and *Astronidium pickeringii* (21%). Average burrow dimensions measured 47.4 ± 4.7 cm (S.E.) wide, 40.5 ± 4.2 cm (S.E.) tall, and 79.2 ± 8.9 cm (S.E.) long. Average canopy cover at burrow sites was 67.8% $\pm$ 31.2 S.D., and 84% of burrow plots were classified as having a closed canopy cover (> 25%). In comparison, average canopy cover at random sites was 22.2% $\pm$ 35.3 S.D. Ferns were the most prevalent ground cover

vegetation, having the highest percent cover in 48% of nest plots. The next most prevalent ground cover was *Freycinetia*, having the highest percent cover in 28% of nest plots. Within the 3 m plots, ferns covered an average of 26.5%, and *Freycinetia* covered an average of 24.0%.

Burrow Habitat Models

The final binary logistic regression model was built using the independent explanatory variables of altitude, aspect, canopy cover type, dominant ground cover type, dominant canopy species, number of trees, and number of tree ferns (Table 1). The best model describing the characteristics of the Tahiti petrel burrows included both canopy cover type and altitude, and explained 52.4% of the variance, correctly predicting whether the plot would contain a petrel burrow 83.9% of the time ($\chi^2 = 27.74$, $df = 2$, $P < 0.001$). Of the top models based on AIC values, the one variable and three variable models were not well fitted (Hosmer – Lemeshow GOF $P \leq 0.05$, Table 1). Canopy cover was the most important variable in determining if a plot contained a burrow, with closed canopies much more likely to have a burrow present (OR = 40.6, df = 1, $P < 0.001$). In addition, higher altitude also had a significant effect on whether a plot contained a petrel burrow (OR = 1.0, df = 1, $P = 0.036$). The ground cover type was not important for determining burrow location, because burrows were overwhelmingly associated with closed canopies. The dominant canopy species was not important for determining burrow location, because, regardless of species, the presence of taller trees or tree ferns provided structure for the burrows underneath.

Habitat Availability on Ta‘ū

Overall, I classified 774.72 ha of habitat. Of the visible habitat, 494.22 ha was classified as tree-covered (63.79%), and 249.02 was classified as *Freycinetia* or fern-covered (32.14%) (Figure 4). All closed canopy cover habitat plots were within 3 m (GPS error) of tree classified pixels, and accuracy of estimated canopy cover in the classified plots was 84.5% indicating that the supervised maximum likelihood classification was accurate. There was a clear difference in the habitat composition between the east and west sides of the summit habitat, with the west side containing a much higher percentage of trees (80.02%) than the east side (46.50%). Of the final habitat suitability index, 254.1 ha (32.8%) of the total montane habitat on Ta‘ū was determined to be suitable for Tahiti petrel breeding (category 1 and 2; Figure 5).

Discussion

The presence of canopy species was the most important factor for determining the presence of Tahiti petrels across the summit of Ta‘ū. Additionally, there was a large amount of variation in the distribution of canopy species across the summit habitat over 650 m, and this variation likely has a significant impact on the population and distribution of Tahiti petrels. Trees and canopy cover were the most important components of habitat for Tahiti petrels.

All Tahiti petrel burrows were found underneath the exposed root systems of trees and tree ferns within the summit montane habitat, similar the results of previous studies of Tahiti petrels in this colony (Amerson et al. 1982, O’Connor and Rauzon 2004). Because of the Tahiti petrel’s reliance on trees and tree ferns for suitable nesting habitat, and the general tendency for Procellariiform seabirds to exhibit high nest site fidelity (Bried and Jouventin 2001), changes

to the amount of tree-covered habitat on Ta‘ū would be likely to impact the breeding populations of Tahiti petrels by reducing nest site availability and decreasing the carrying capacity of the montane habitat. Both American Samoa and Independent Samoa have been hit by many significant storms and hurricanes, including at least 39 hurricanes between 1831 and 1926 (Amerson et al. 1982). Most recently, Ta‘ū was hit by hurricane Olaf in 2005, which caused significant structural damage to the forests over the entire island (Webb et al. 2014). While the damage to trees and tree ferns within the summit montane habitat was undocumented, it is likely that it was similar or greater than documented damage in the lower elevation forests during previous hurricanes (Whistler 1992). While the Tahiti petrel population on Ta‘ū has likely adapted to the frequent habitat disturbance, any future increases in the amount of disturbance or long-term changes to the montane habitat structure could negatively impact seabird populations.

Extensive work has been conducted to document the negative impacts to Procellariiform populations from invasive animals such as rats, cats, dogs, and mongoose (Warham 1990, Croxall et al. 2012). However, additional work should be focused on determining the direct impacts to populations from habitat loss and change (Dolman and Sutherland 1995). Sub-tropical island breeding petrels are particularly susceptible to threats and extinction (Warham 1990, Carlile et al. 2003), including the loss of habitat (BirdLife International 2000). In addition, tropical cyclone intensity has been increasing over the last 30 years, which may lead to greater habitat loss (Emanuel 2005). Habitat degradation is one of the principal threats to seabirds worldwide (Croxall et al. 2012), and determining the relative

impacts on seabird populations from both anthropogenic and natural sources is important for properly informing management plans.

A large difference was found in the amount of tree and tree fern cover between the east and west sides of the summit habitat above 650 m on Ta‘ū. Canopy cover on the west side of the summit was 80.0% versus 46.5% on the east side of the summit (Figure 4). The reasons for the difference in vegetation structure between the two sides of the summit is unclear. Whistler (1992) characterized the entire area as summit vegetation, but noted the difference between the vegetation on either side of the summit, describing the east side of the summit as summit scrub, with smaller, sparse tree coverage. In an in-depth vegetation survey of Ta‘ū, Cole et al. (1988) classified the entire summit area as moss forest, with no distinction between the east and west sides of the summit. One possible explanation for the observed variation in spatial habitat composition could be differences in localized groundwater impounding or prevailing wind conditions (Bentley 1975, Amerson et al. 1982, Izuka 2005). The prevailing easterly trade winds could also be responsible for the stunted scrub habitat on the eastern windward side, while the leeward side of the summit habitat’s lower wind conditions would allow for larger trees to grow.

The findings demonstrate the importance of trees and other forest canopy species in providing nesting habitat for Tahiti petrels breeding on Ta‘ū. Samoa is within a high likelihood hurricane corridor and is particularly susceptible to impacts from large storm systems (Kodama and Businger 1998, Meehl et al. 2000). As a result, there is a high potential for future habitat damage and change. Understanding how these future habitat changes affect breeding populations of Tahiti petrels and other Procellariiform seabirds is important to determine the

future conservation and management needs of these species if rates of disturbance increase. This study highlights the importance of determining suitable habitat when undergoing conservation planning as it allows management actions to be targeted towards areas where species of interest are most likely to be.

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Tables

Table 4.1. Goodness of fit and selection results for the best binary logistic models explaining Tahiti petrel nesting habitat preferences. The selected best model was the 2 variable model (Canopy type + Altitude) due to a high r^2 combined with a low AIC value for a model which was well fitted using the Hosmer – Lemeshow Goodness of Fit test.

Model	r^2	AIC	ΔAIC	H-L GOF *P*
Canopy type	0.441	10.6	0.0	<0.001
Canopy height	0.131	43.7	33.1	0.027
Canopy type + Altitude	0.524	51.9	41.3	**0.894**
Canopy type + Canopy height	0.452	62.5	51.9	**0.509**
Canopy type + Altitude + Dominant vegetation type	0.556	53.1	42.5	0.037

Figures

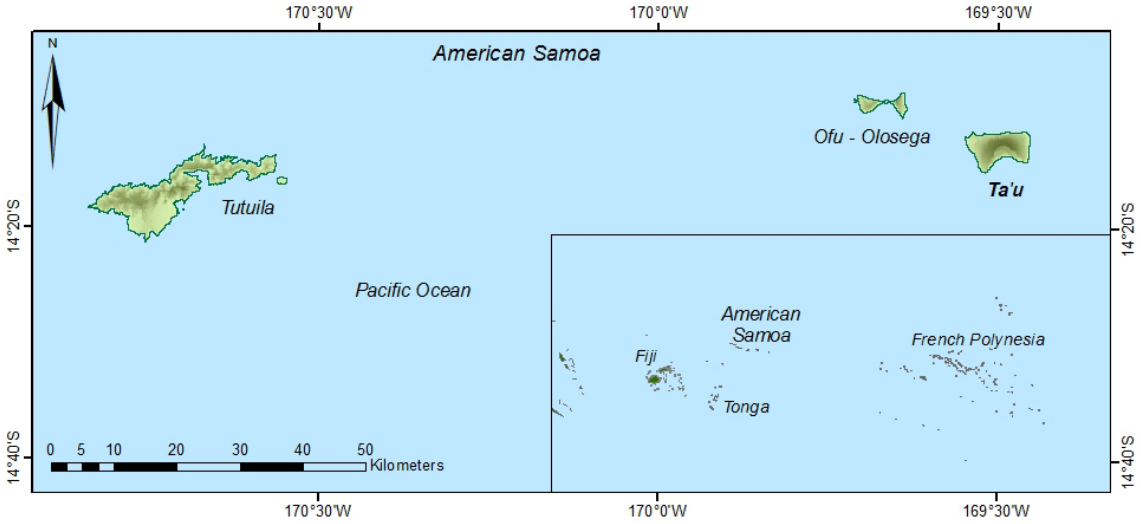

Figure 4.1. Map of the main islands of American Samoa including Tutuila, Ofu-Olosega, and Taʻū. Shown inset is American Samoa relative to other islands in the South Pacific Ocean.

Figure 4.2. Tahiti petrel burrow with a pair of dueting petrels present. The structure of the burrow is provided by the root structure of the overhead trees and the ground is free of vegetation.

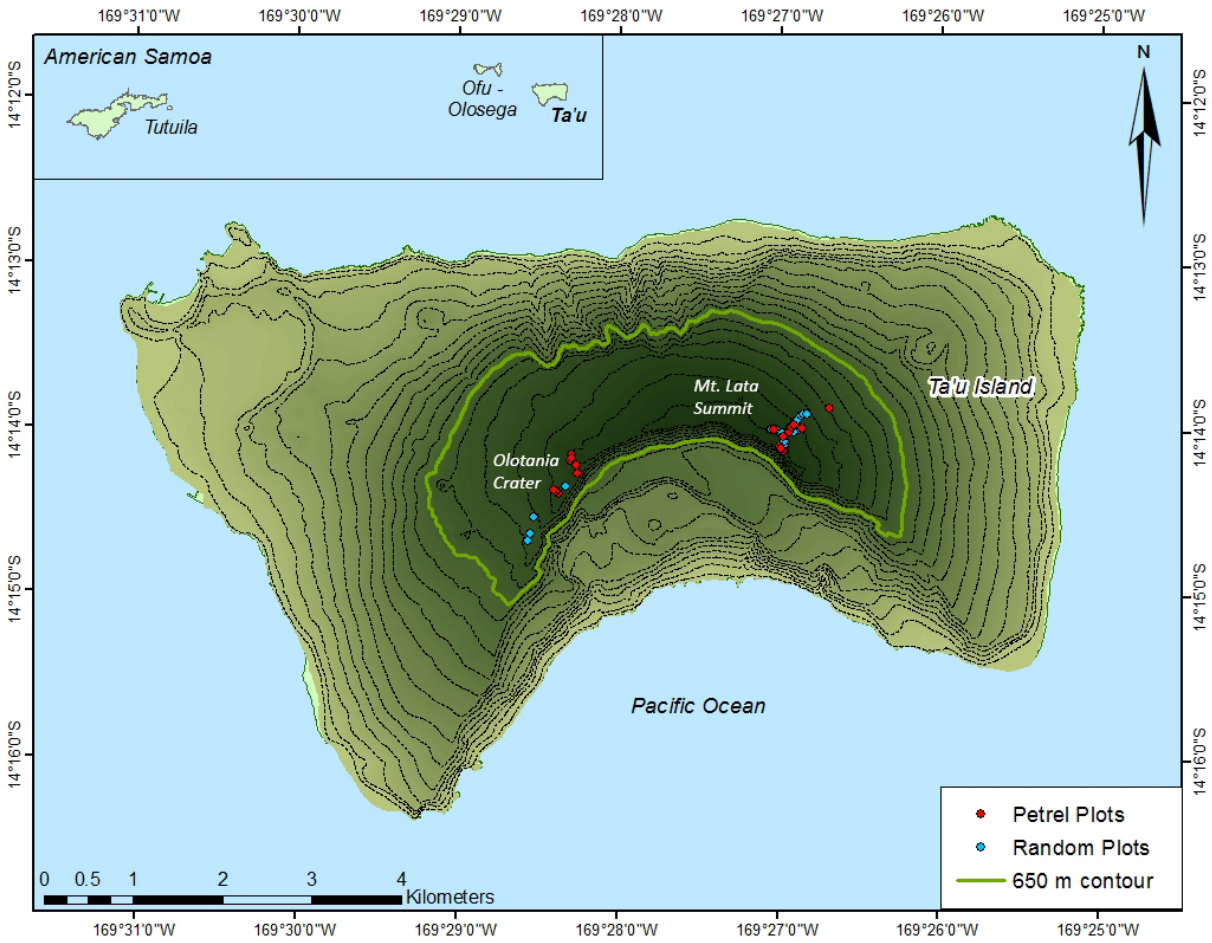

Figure 4.3. Map of Ta‘ū Island, American Samoa, showing the location of petrel burrow (red dots) and random habitat classification plots (blue dots). Also shown is the 650 m contour line (green) delineating montane rainforest habitat and black contour lines delineating every 50 m of elevation.

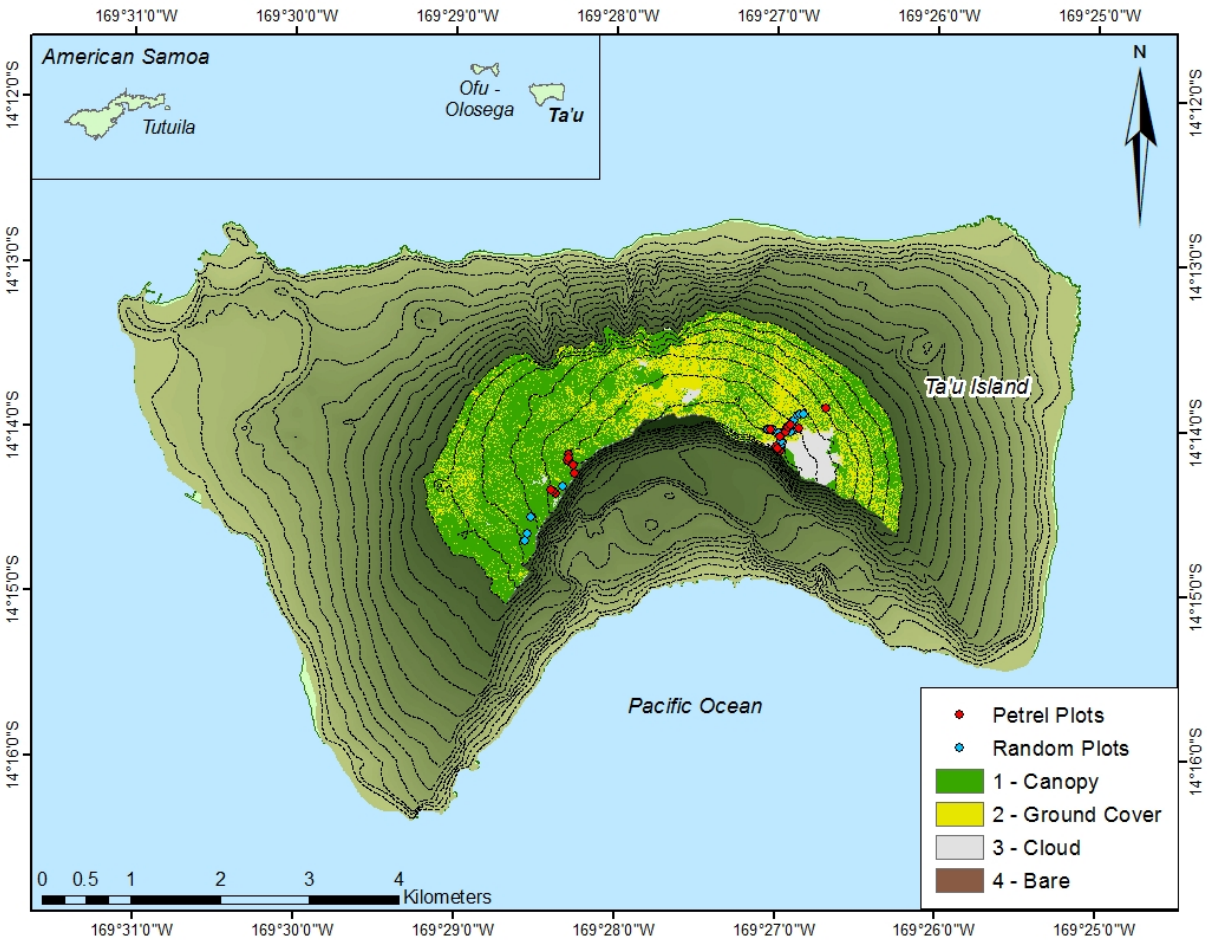

Figure 4.4. Map of Ta‘ū Island with the summit montane habitat classified by the presence of trees (bright green) or open ground cover (yellow). Also show is the locations of habitat classification plots (both random and petrel burrow).

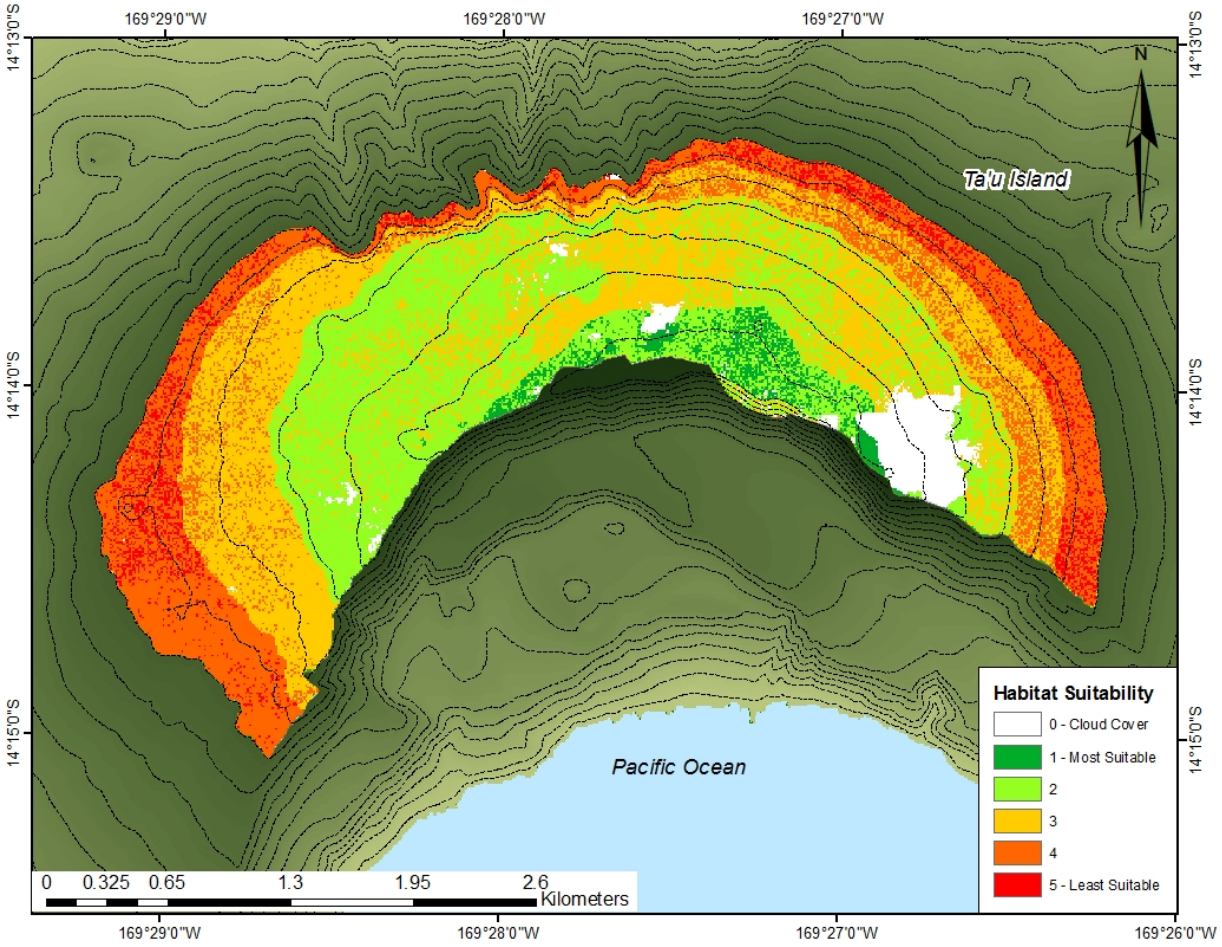

Figure 4.5. Map of Ta‘ū Island summit montane habitat classified by habitat suitability. The most suitable habitat (categories 1, 2) is presented in green, and the least suitable habitat (categories 4, 5) is presented in red.

CHAPTER 5. CONCLUSIONS

Development of Novel Tools to Investigate the Ecology of Cryptic, Tropical Seabirds

In this dissertation, I investigated how secretive, tropical Procellariiform seabirds use high montane forest habitat on the remote island of Taʻū in American Samoa. Because the summit montane habitat of Taʻū is the embodiment of a remote, inaccessible ecosystem, and the seabirds nesting within this habitat are nocturnal burrow nesters, innovative methods for investigating their ecology were necessary. In Chapter 2, I investigated the ability of automated recording units (ARU) to detect the suite of seabirds present over different habitat and wind conditions. I determined how the differences in these conditions affected the maximum distance that calls could be detected from, and compared different recording sensors and methods for call detection. In Chapter 3, I used these ARUs to investigate the distribution and abundance of three Procellariiform seabirds (Tahiti petrel, Tropical shearwater, Herald petrel) across the summit area of Taʻū. Through the use of these acoustic survey methods I was able to determine patterns in the distribution and relative abundance of these species. Additionally, I was able to reveal temporal patterns over multiple scales in colony attendance of these poorly studied seabirds. Finally, in Chapter 4 I investigated the nesting habitat associations of the most prevalent bird on the summit of Taʻū, the Tahiti petrel. Through a Species Distribution Modeling technique I determined the most important habitat characteristics determining the presence of Tahiti petrel burrows were the presence of canopy cover and higher altitude, and through GIS remote sensing techniques I determined the amount of available suitable habitat across the

summit region of Ta‘ū. The information in Chapter 4 moves our knowledge of the terrestrial breeding habitat of this species forward.

Overall, the research findings presented here advances our knowledge of the ecology, behavior, and life history of several data-deficient seabird species within a generally poorly studied region in the South Pacific. These findings have implications for the management of these species and their montane habitats in American Samoa because they identify patterns in spatial and temporal habitat use, in addition to the distribution of suitable habitat for the Tahiti petrel. The data presented in this dissertation help to show the importance of this montane habitat as well as providing a guide for future research into the status and conservation needs of the seabirds nesting on Ta‘ū. Furthermore, the information about the use of ARUs provides evidence of their usefulness, particularly in extremely challenging environments that experience a wide range of environmental and weather conditions.

Summary of Conclusions and Results

Passive Acoustic Recorder Detection Probabilities

Automated Recording Units have the ability to significantly increase our understanding of the ecology, behavior, and phenology of seabirds at their nesting colonies however the ability of these sensors to detect seabird calls is highly influenced by the local weather and environmental conditions. On the island of Ta‘ū, Song Meter ARU detection range varied from less than 10 m in high wind conditions for Tropical shearwater calls, up to 100 m for mid frequency tones in low wind conditions. Both the low frequency components, and call features

without clear tones or harmonics were difficult to detect, particularly when masked by low frequency wind noise. Additionally, detection range was significantly greater in low wind conditions for newer Song Meter SM4 sensors, and for manual call detection methods, highlighting the importance of standardization of equipment and methods across studies to allow for spatial and temporal comparisons of results. Finally, detection range can vary significantly on very short time scales as local weather conditions change, emphasizing the need to pair ARUs with in situ weather data recorders in order to determine seabird densities and population estimates.

Patterns of Seabird Habitat Use on Ta‘ū

The summit montane region of Ta‘ū provides habitat to at least three species of Procellariiformes seabirds: Tahiti petrel, Herald petrel, and Tropical shearwater. However, there are differences in the spatiotemporal distribution of these species across the summit habitat. Tahiti petrels are distributed across both sides of the Ta‘ū summit, while Tropical shearwaters and Herald petrels are preferentially found on the leeward (west) side of the summit. Additionally, an unknown *Pterodroma* like call was detected on the west side of the summit, along with a potential Newell's shearwater, indicating that additional species may be both breeding and visiting the Ta‘ū summit habitat. Both Tahiti petrels and Tropical shearwaters were detected throughout the study period, indicating that there are no clearly defined nesting seasons for these species on Ta‘ū. However, different temporal spikes in acoustic activity for both species indicate that there may be temporally differentiated increased breeding activity for both species. Additionally, there were no patterns in colony attendance correlated with the

presence of the full moon, contrary to the behavior of many other Procellariiform species at other locations.

Tahiti Petrel Habitat Preferences

Tahiti petrels are the most prevalent breeding seabird within the summit montane habitat of Ta‘ū and their preferential breeding habitat is strongly influenced by the presence of canopy species such as trees and tree ferns which provide structure for petrel burrows. While petrel burrows are strongly linked to the presence of canopy species, the vegetation structure of the summit montane and summit scrub region is highly variable. Particularly, significant variation exists in the distribution of canopy species across the summit of Ta‘ū and this structure is likely constantly in a state of change due to natural disturbance events. Particularly, the west side of the summit habitat contains a higher proportion of canopy species coverage. This natural change may have impacts on the interannual variation of breeding Tahiti petrels.

Future Work

A significant amount of work remains to be done, both in understanding the utility of ARUs for seabird research, and in understanding how the nesting preferences of tropical Procellariiformes seabirds are shaped and influenced by the structure and characteristics of the environment. From a technical perspective, understanding the possibilities and limitations of ARUs is important for advancing their use in seabird research. As was detailed in Chapter 2, the use of ARUs for seabird research have thus far been mostly used to determine the presence of species, and indices of relative abundance through the detection of call rates. To transform the

use of these acoustic tools to determine abundance estimates that can be compared across sites and over time requires an understanding of both the acoustic calling behavior of the species of interest, and the ability of the ARU to detect any given call. This transformative process has already occurred for the use of acoustics in the field of marine mammal science, but has only just started for seabird research. Future effort should focus on determining the fine time scale effects of wind, rain, and other noisy environmental conditions on the detection distances of ARUs through further field experiments.

Multiple issues exist that make using ARUs for seabird research in terrestrial applications more difficult than for the study of marine mammals in marine applications. First, as the research presented in Chapter 2 demonstrated, environmental conditions, and in particular, wind significantly impacts the range at which a call can be detected by the ARU. Additionally, those environmental conditions can vary drastically and quickly, leading to fine time scale variations in the detection range of the ARU. Second, the ability of the ARU to detect a call is unsurprisingly very species and call specific. While it is generally understood that further work is needed to determine the call rates of the target species, additional information about their acoustic behavior must be understood. For example, the use of different call types, variation between calls due to sex and age, and differences in acoustic behavior throughout the breeding cycle must be understood. Finally, in the space of the colony, birds are calling both from a static position within a burrow or nest and are calling within flight and work must be done to be able to reliably separate those two different acoustic data sources. Overall, this highlights the need to invest further time and effort in understanding the behavior and life history of a species in order to maximize the use of these acoustic tools which will only continue

to increase in value to the seabird research community. Of great value would be for colony based seabird studies to collect data on call rates and timing within the breeding cycle of species and to deposit this information in an open access database which would aid in the utility of ARUs around the world.

This dissertation examined the use of montane forest nesting habitat by Procellariiformes seabirds, primarily the Tahiti petrel (*Pseudobulweria rostrata*) and examined the habitat characteristics that determine their distribution. Extensive research has been conducted examining the habitat associations that drive the distribution of seabirds across large areas at sea, however much less work has been conducted to examine the distribution of seabirds on a finer spatial scale across their breeding habitats and colonies. Partially, this is due to the difficulties associated with determining nesting habitat preferences of seabirds where coloniality, social effects, and site fidelity confound the direct environmental and habitat variables that can drive nesting distribution. However, further work to understand how habitat structure and variability influence the realized niche of the Tahiti petrel has the potential to have profound impacts on how this species is understood and managed. Future work should focus on tracking change in the habitat structure over time, and how this habitat change affects the breeding success of individual petrel nests.

The main limitations of the work presented in this dissertation are ones that would be expected from working in such a remote and challenging environment. The lack of infrastructure and support for science led to many changes in my expectations of what could be achieved throughout the course of this work. However, I think it is important to recognize that even with better support, studying these species in these habitats is a difficult proposition.

Avoiding negative impacts to the nesting environment of these seabirds is vitally important and more intensive study of these birds certainly has the potential for increased damage and change to the summit montane environment. The need to balance scientific progress with environmental protection is a key argument for continuing the development of new and better technologies, tools, and methods for remotely studying wildlife. Advances in locational tracking technology, acoustic sensors, remote camera technology, unmanned aircraft systems, and remote sensing all stand to have greater impacts on wildlife ecology science in the years to come.

The island of Taʻū is a special place, its remote summit provides potentially significant breeding habitat to not only Tahiti petrels, but to Tropical shearwaters (*Puffinus bailloni*), Herald petrels (*Pterodroma heraldica*), and other species. The seabirds on Taʻū exist seemingly largely separated from large anthropogenic threats, yet they are threatened by invasive species, habitat change, and potentially other unknown threats both at land and at sea. Understanding the ecology of these birds, and this ecosystem further will provide opportunities to not only better conserve and manage these species in American Samoa, and will result in increases of understanding of other Procellariiform seabirds, and remote island ecosystems. There is so much more in the world to explore and understand.